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- (71) **Applicants:** **UNIVERSAL DISPLAY CORPORATION** [US/US]; 375 Phillips Boulevard, Ewing, New Jersey 08618 (US). **TOSOH CORPORATION** [JP/JP]; 3-8-2, Shiba, Minato-ku, Tokyo, 105-8623 (JP).
- (72) **Inventors:** **YAMAMOTO, Hitoshi**; 375 Phillips Boulevard, Ewing, New Jersey 08618 (US). **WEAVER, Michael Stuart**; 375 Phillips Boulevard, Ewing, New Jersey 08618 (US). **UCHIDA, Naoki**; Ayase-shi, Kanagawa (JP). **TANAKA, Tsuyoshi**; Ayase-shi, Kanagawa (JP). **NOMURA, Keisuke**; Ayase-shi, Kanagawa (JP). **ARAI, Nobumichi**; Ayase-shi, Kanagawa (JP). **IIDA, Takashi**; Ayase-shi, Kanagawa (JP). **HONMA, Yoko**; Ayase-shi, Kanagawa (JP).
- (74) **Agents:** **DAVOUDIAN, Keyvan** et al.; Pillsbury Winthrop Shaw Pittman LLP, 725 South Figueroa Street, Suite 2800, Los Angeles, California 90017-5406 (US).

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(54) **Title:** PHOSPHORESCENT OLED DEVICES

(57) **Abstract:** An organic light-emitting diode (OLED) device includes an emissive layer having a host material and a phosphorescent dopant, the host material including a benzo-fused thiophene and the phosphorescent dopant including a heteroleptic transition metal complex having extended conjugation, a hole blocking layer disposed on the emissive layer, the hole blocking layer including a hole blocking material, an electron transport layer disposed on the hole blocking layer, the OLED device having a luminous efficacy of at least about 40 lm/W at 1,000 cd/m² (nits).



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PHOSPHORESCENT OLED DEVICES

BACKGROUND

[0001] Embodiments disclosed herein relate to organic light emitting diode devices (OLEDs).

5 In particular, embodiments disclosed herein relate to a combination of device materials to provide OLED devices having enhanced luminous efficacy, low voltage, and increased device lifetime.

[0002] Generally, an OLED comprises at least one organic layer disposed between and electrically connected to an anode and a cathode. When a current is applied, the anode

10 injects holes and the cathode injects electrons into the organic layer(s). The injected holes and electrons each migrate toward the oppositely charged electrode. When an electron and hole localize on the same molecule, an "exciton," which is a localized electron-hole pair having an excited energy state, is formed. Light is emitted when the exciton relaxes via a photoemissive mechanism. In some cases, the exciton may be localized on an excimer or an
15 exciplex. Non-radiative mechanisms, such as thermal relaxation, may also occur, but are generally considered undesirable.

BRIEF DESCRIPTION OF THE FIGURES

20 [0003] FIG. 1 is a schematic drawing showing an outline constitution of one example of the OLED according to one embodiment of the present disclosure. The drawing is not drawn to scale.

[0004] FIG. 2 shows an inverted OLED according to another embodiment of the present disclosure.

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[0005] FIG. 3 shows an exemplary multilayered OLED device in accordance with embodiments disclosed herein.

SUMMARY

30 [0006] In some aspects, embodiments disclosed herein relate to organic light-emitting diode (OLED) devices comprising an emissive layer comprising a host material and a phosphorescent dopant, wherein the host material comprises a benzo-fused thiophene and the phosphorescent dopant comprises a heteroleptic transition metal complex having extended conjugation, a hole blocking layer disposed on the emissive layer, the hole blocking
35 layer comprising a hole blocking material, an electron transport layer disposed on the hole blocking layer, wherein the OLED device has a luminous efficacy of at least about 40 lm/W at 1,000 cd/m² (nits).

DETAILED DESCRIPTION

[0007] Opto-electronic devices that make use of organic materials are becoming increasingly desirable for a number of reasons. Many of the materials used to make such devices are relatively inexpensive, so organic opto-electronic devices have the potential for cost advantages over inorganic devices. In addition, the inherent properties of organic materials, such as their flexibility, may make them well suited for particular applications such as fabrication on a flexible substrate. Examples of organic opto-electronic devices include organic light emitting devices (OLEDs), organic phototransistors, organic photovoltaic cells, and organic photodetectors. For OLEDs, the organic materials may have performance advantages over conventional materials. For example, the wavelength at which an organic emissive layer emits light may generally be readily tuned with appropriate dopants.

[0008] OLEDs make use of thin organic films that emit light when voltage is applied across the device. OLEDs are becoming an increasingly utilized technology in applications such as flat panel displays, illumination, and backlighting. Several OLED materials and configurations are described in U.S. Pat. Nos. 5,844,363, 6,303,238, and 5,707,745, which are incorporated herein by reference in their entirety.

[0009] One application for phosphorescent emissive molecules is a full color display. Industry standards for such a display call for pixels adapted to emit particular colors, referred to as "saturated" colors. In particular, these standards call for saturated red, green, and blue pixels. Color may be measured using CIE coordinates, which are well known to the art.

[0010] Early OLEDs used emissive molecules that emitted light from their singlet states ("fluorescence") as disclosed, for example, in U.S. Pat. No. 4,769,292, which is incorporated by reference in its entirety. Fluorescent emission generally occurs in a time frame of less than 10 nanoseconds.

[0011] More recently, OLEDs having emissive materials that emit light from triplet states ("phosphorescence") have been demonstrated. Baldo et al., "Highly Efficient Phosphorescent Emission from Organic Electroluminescent Devices," *Nature*, vol. 395, 151-154, 1998; ("Baldo-I") and Baldo et al., "Very high-efficiency green organic light-emitting devices based on electrophosphorescence," *Appl. Phys. Lett.*, vol. 75, No. 3, 4-6 (1999) ("Baldo-II"), which are incorporated by reference in their entireties.

[0012] Phosphorescence may be referred to as a "forbidden" transition because the transition requires a change in spin states, and quantum mechanics indicates that such a transition is not favored. As a result, phosphorescence generally occurs in a time frame exceeding at least 10 nanoseconds, and typically greater than 100 nanoseconds. If the natural radiative lifetime of phosphorescence is too long, triplets may decay by a non-radiative mechanism, such that no light is emitted. Organic phosphorescence is also often observed in molecules containing heteroatoms with unshared pairs of electrons at very low temperatures. 2,2'-bipyridine is such

a molecule. Non-radiative decay mechanisms are typically temperature dependent, such that an organic material that exhibits phosphorescence at liquid nitrogen temperatures typically does not exhibit phosphorescence at room temperature. But, as demonstrated by Baldo, this problem may be addressed by selecting phosphorescent compounds that do phosphoresce at room temperature. Representative emissive layers include doped or un-doped phosphorescent organometallic materials such as disclosed in U.S. Pat. Nos. 6,303,238 and 6,310,360; U.S. Patent Application Publication Nos. 2002-0034656; 2002-0182441; 2003-0072964; and WO-02/074015.

[0013] Generally, the excitons in an OLED are believed to be created in a ratio of about 3:1, i.e., approximately 75% triplets and 25% singlets. See, Adachi et al., "Nearly 100% Internal Phosphorescent Efficiency In An Organic Light Emitting Device," J. Appl. Phys., 90, 5048 (2001), which is incorporated by reference in its entirety. In many cases, singlet excitons may readily transfer their energy to triplet excited states via "intersystem crossing," whereas triplet excitons may not readily transfer their energy to singlet excited states. As a result, 100% internal quantum efficiency is theoretically possible with phosphorescent OLEDs. In a fluorescent device, the energy of triplet excitons is generally lost to radiationless decay processes that heat-up the device, resulting in much lower internal quantum efficiencies. OLEDs utilizing phosphorescent materials that emit from triplet excited states are disclosed, for example, in U.S. Pat. No. 6,303,238, which is incorporated by reference in its entirety.

[0014] Phosphorescence may be preceded by a transition from a triplet excited state to an intermediate non-triplet state from which the emissive decay occurs. For example, organic molecules coordinated to lanthanide elements often phosphoresce from excited states localized on the lanthanide metal. However, such materials do not phosphoresce directly from a triplet excited state but instead emit from an atomic excited state centered on the lanthanide metal ion. The europium diketonate complexes illustrate one group of these types of species.

[0015] Phosphorescence from triplets can be enhanced over fluorescence by confining, such as through bonding, the organic molecule in close proximity to an atom of high atomic number. This phenomenon, called the heavy atom effect, is created by a mechanism known as spin-orbit coupling. Such a phosphorescent transition may be observed from an excited metal-to-ligand charge transfer (MLCT) state of an organometallic molecule such as tris(2-phenylpyridine)iridium(III).

[0016] As used herein, the term "triplet energy" refers to an energy corresponding to the highest energy feature discernable in the phosphorescence spectrum of a given material. The highest energy feature is not necessarily the peak having the greatest intensity in the phosphorescence spectrum, and could, for example, be a local maximum of a clear shoulder on the high energy side of such a peak.

[0017] FIG. 1 shows an organic light emitting device 100. The figures are not necessarily drawn to scale. Device 100 may include a substrate 110, an anode 115, a hole injection layer

120, a hole transport layer 125, an electron blocking layer 130, an emissive layer 135, a hole blocking layer 140, an electron transport layer 145, an electron injection layer 150, a protective layer 155, a cathode 160, and a barrier layer 170. Cathode 160 is a compound cathode having a first conductive layer 162 and a second conductive layer 164. Device 100 may be fabricated by depositing the layers described, in order. The properties and functions of these various layers, as well as example materials, are described in more detail in US 7,279,704 at cols. 6-10, which are incorporated by reference.

[0018] More examples for each of these layers are available. For example, a flexible and transparent substrate-anode combination is disclosed in U.S. Pat. No. 5,844,363, which is incorporated by reference in its entirety. An example of a p-doped hole transport layer is m-MTDATA doped with F₄-TCNQ at a molar ratio of 50:1, as disclosed in U.S. Patent Application Publication No. 2003/0230980, which is incorporated by reference in its entirety. Examples of emissive and host materials are disclosed in U.S. Pat. No. 6,303,238 to Thompson et al., which is incorporated by reference in its entirety. An example of an n-doped electron transport layer is BPhen doped with Li at a molar ratio of 1:1, as disclosed in U.S. Patent Application Publication No. 2003/0230980, which is incorporated by reference in its entirety. U.S. Pat. Nos. 5,703,436 and 5,707,745, which are incorporated by reference in their entireties, disclose examples of cathodes including compound cathodes having a thin layer of metal such as Mg:Ag with an overlying transparent, electrically-conductive, sputter-deposited ITO layer. The theory and use of blocking layers is described in more detail in U.S. Pat. No. 6,097,147 and U.S. Patent Application Publication No. 2003/0230980, which are incorporated by reference in their entireties. Examples of injection layers are provided in U.S. Patent Application Publication No. 2004/0174116, which is incorporated by reference in its entirety. A description of protective layers may be found in U.S. Patent Application Publication No. 2004/0174116, which is incorporated by reference in its entirety.

[0019] FIG. 2 shows an inverted OLED 200. The device includes a substrate 210, a cathode 215, an emissive layer 220, a hole transport layer 225, and an anode 230. Device 200 may be fabricated by depositing the layers described, in order. Because the most common OLED configuration has a cathode disposed over the anode, and device 200 has cathode 215 disposed under anode 230, device 200 may be referred to as an "inverted" OLED. Materials similar to those described with respect to device 100 may be used in the corresponding layers of device 200. FIG. 2 provides one example of how some layers may be omitted from the structure of device 100.

[0020] Devices fabricated in accordance with embodiments disclosed herein may further optionally comprise a barrier layer. One purpose of the barrier layer is to protect the electrodes and organic layers from damaging exposure to harmful species in the environment including moisture, vapor and/or gases, etc. The barrier layer may be deposited over, under or next to a substrate, an electrode, or over any other parts of a device including an edge. The

barrier layer may comprise a single layer, or multiple layers. The barrier layer may be formed by various known chemical vapor deposition techniques and may include compositions having a single phase as well as compositions having multiple phases. Any suitable material or combination of materials may be used for the barrier layer. The barrier layer may incorporate an inorganic or an organic compound or both. In some embodiments, the barrier layer comprises a mixture of a polymeric material and a non-polymeric material as described in U.S. Pat. No. 7,968,146, PCT Pat. Application Nos. PCT/US2007/023098 and PCT/US2009/042829, which are herein incorporated by reference in their entireties. To be considered a "mixture", the aforesaid polymeric and non-polymeric materials comprising the barrier layer should be deposited under the same reaction conditions and/or at the same time. The weight ratio of polymeric to non-polymeric material may be in the range of 95:5 to 5:95. The polymeric material and the non-polymeric material may be created from the same precursor material. In one example, the mixture of a polymeric material and a non-polymeric material consists essentially of polymeric silicon and inorganic silicon.

[0021] Embodiments disclosed herein provide phosphorescent organic light emitting devices (PHOLED) having high power efficiency and operational stability. Superior power efficacy and long device lifetime were achieved via a synergistic combination of materials within the devices. In particular, a combination of appropriate host material, phosphorescent dopant and electron transport material are disclosed herein to provide devices with improved lifetimes as measured by LT97 (time for luminance to decrease to 97% of its initial level) of about 51 hours at 10,000 cd/m² (nits). Devices disclosed herein may also achieve power efficacies of about 61 lm/W. These device characteristics are obtained at low voltage making the combination of materials unexpectedly superior to state of the art devices. These and other advantages will be apparent to those skilled in the art.

In embodiments, there are provided organic light-emitting diode (OLED) devices comprising an emissive layer comprising a host material and a phosphorescent dopant, wherein the host material comprises a benzo-fused thiophene and the phosphorescent dopant comprises a heteroleptic transition metal complex having extended conjugation and an electron transport layer disposed on the hole blocking layer, wherein the OLED device has a luminous efficacy of at least about 40 lm/W at 1,000 cd/m² (nits). In embodiments, such devices may further comprise a hole blocking layer disposed between the emissive layer and the electron transport layer, the hole blocking layer comprising a hole blocking material that may be the same or different from the host material in the emissive layer. In some such embodiments the hole blocking material comprises the same benzo-fused thiophene compound as the host material.

[0022] Although the terms used herein are generally intended to have their ordinary meaning as understood by those skilled in the art, the following definitions are nonetheless provided:

[0023] As used herein, “heteroleptic” means a complex having at least two different ligands.

[0024] As used herein, “extended conjugation” refers to an extended array of pi bonds capable of distribution of electron density over many atoms.

[0025] As used herein, “luminous efficacy” refers to a measure of how well a light source produces visible light and is generally computed as the ratio of luminous flux to power.

[0026] The terms halo, halogen, alkyl, cycloalkyl, alkenyl, alkynyl, aralkyl, heterocyclic group, aryl, aromatic group, and heteroaryl are known to the art, but are defined here for ease of reference.

[0027] The term “halo” or “halogen” as used herein includes fluorine, chlorine, bromine and iodine.

[0028] The term “alkyl” as used herein contemplates both straight and branched chain alkyl radicals. Exemplary alkyl groups may contain from one to fifteen carbon atoms and includes methyl, ethyl, propyl, isopropyl, butyl, isobutyl, tert-butyl, and the like. Additionally, the alkyl group may be optionally substituted with one or more substituents selected from halo, CN, CO₂R, C(O)R, NR₂, cyclic-amino, NO₂, and OR, wherein each R is independently selected from H, alkyl, alkenyl, alkynyl, aralkyl, aryl and heteroaryl.

[0029] The term “cycloalkyl” as used herein contemplates cyclic alkyl radicals. Exemplary cycloalkyl groups include those containing 3 to 7 carbon atoms and includes cyclopropyl, cyclopentyl, cyclohexyl, and the like. Additionally, the cycloalkyl group may be optionally substituted with one or more substituents selected from halo, CN, CO₂R, C(O)R, NR₂, cyclic-amino, NO₂, and OR.

[0030] The term “alkenyl” as used herein contemplates both straight and branched chain alkene radicals. Exemplary alkenyl groups include those containing two to fifteen carbon atoms. Additionally, the alkenyl group may be optionally substituted with one or more substituents selected from halo, CN, CO₂R, C(O)R, NR₂, cyclic-amino, NO₂, and OR.

[0031] The term “alkynyl” as used herein contemplates both straight and branched chain alkyne radicals. Exemplary alkyl groups include those containing two to fifteen carbon atoms. Additionally, the alkynyl group may be optionally substituted with one or more substituents selected from halo, CN, CO₂R, C(O)R, NR₂, cyclic-amino, NO₂, and OR.

[0032] The terms “aralkyl” as used herein contemplates an alkyl group that has as a substituent an aromatic group. Additionally, the aralkyl group may be optionally substituted on the aryl with one or more substituents selected from halo, CN, CO₂R, C(O)R, NR₂, cyclic-amino, NO₂, and OR.

[0033] The term “heterocyclic group” as used herein contemplates non-aromatic cyclic radicals. Exemplary heterocyclic groups include those containing 3 or 7 ring atoms which includes at least one hetero atom, and includes cyclic amines such as morpholino, piperdino, pyrrolidino, and the like, and cyclic ethers, such as tetrahydrofuran, tetrahydropyran, and the

like. Additionally, the heterocyclic group may be optionally substituted with one or more substituents selected from halo, CN, CO₂R, C(O)R, NR₂, cyclic-amino, NO₂, and OR.

[0034] The term "aryl" or "aromatic group" as used herein contemplates single-ring groups and polycyclic ring systems. The polycyclic rings may have two or more rings in which two carbons are common by two adjoining rings (the rings are "fused") wherein at least one of the rings is aromatic, e.g., the other rings can be cycloalkyls, cycloalkenyls, aryl, heterocycles and/or heteroaryls. Additionally, the aryl group may be optionally substituted with one or more substituents selected from halo, CN, CO₂R, C(O)R, NR₂, cyclic-amino, NO₂, and OR.

[0035] The term "heteroaryl" as used herein contemplates single-ring hetero-aromatic groups that may include from one to three heteroatoms, for example, pyrrole, furan, thiophene, imidazole, oxazole, thiazole, triazole, pyrazole, pyridine, pyrazine and pyrimidine, and the like. The term heteroaryl also includes polycyclic hetero-aromatic systems having two or more rings in which two atoms are common to two adjoining rings (the rings are "fused") wherein at least one of the rings is a heteroaryl, e.g., the other rings can be cycloalkyls, cycloalkenyls, aryl, heterocycles and/or heteroaryls. Additionally, the heteroaryl group may be optionally substituted with one or more substituents selected from halo, CN, CO₂R, C(O)R, NR₂, cyclic-amino, NO₂, and OR.

[0036] As used herein, the term "organic" includes polymeric materials as well as small molecule organic materials that may be used to fabricate organic opto-electronic devices.

"Small molecule" refers to any organic material that is not a polymer, and "small molecules" may actually be quite large. Small molecules may include repeat units in some circumstances. For example, using a long chain alkyl group as a substituent does not remove a molecule from the "small molecule" class. Small molecules may also be incorporated into polymers, for example as a pendent group on a polymer backbone or as a part of the backbone. Small molecules may also serve as the core moiety of a dendrimer, which consists of a series of chemical shells built on the core moiety. The core moiety of a dendrimer may be a fluorescent or phosphorescent small molecule emitter. A dendrimer may be a "small molecule," and it is believed that all dendrimers currently used in the field of OLEDs are small molecules.

[0037] [As used herein, "top" means furthest away from the substrate, while "bottom" means closest to the substrate. Where a first layer is described as "disposed over" a second layer, the first layer is disposed further away from substrate. There may be other layers between the first and second layer, unless it is specified that the first layer is "in contact with" the second layer. For example, a cathode may be described as "disposed over" an anode, even though there are various organic layers in between.

[0038] As used herein, "solution processible" means capable of being dissolved, dispersed, or transported in and/or deposited from a liquid medium, either in solution or suspension form.

[0039] As used herein, and as would be generally understood by one skilled in the art, a first "Highest Occupied Molecular Orbital" (HOMO) or "Lowest Unoccupied Molecular Orbital"

(LUMO) energy level is "greater than" or "higher than" a second HOMO or LUMO energy level if the first energy level is closer to the vacuum energy level. Since ionization potentials (IP) are measured as a negative energy relative to a vacuum level, a higher HOMO energy level corresponds to an IP having a smaller absolute value (an IP that is less negative). Similarly, a higher LUMO energy level corresponds to an electron affinity (EA) having a smaller absolute value (an EA that is less negative). On a conventional energy level diagram, with the vacuum level at the top, the LUMO energy level of a material is higher than the HOMO energy level of the same material. A "higher" HOMO or LUMO energy level appears closer to the top of such a diagram than a "lower" HOMO or LUMO energy level.

[0040] As used herein, and as would be generally understood by one skilled in the art, a first work function is "greater than" or "higher than" a second work function if the first work function has a higher absolute value. Because work functions are generally measured as negative numbers relative to vacuum level, this means that a "higher" work function is more negative. On a conventional energy level diagram, with the vacuum level at the top, a "higher" work function is illustrated as further away from the vacuum level in the downward direction. Thus, the definitions of HOMO and LUMO energy levels follow a different convention than work functions.

[0041] More details on OLEDs, and the definitions described above, can be found in US Pat. No. 7,279,704, which is incorporated herein by reference in its entirety.

[0042] Referring now to Figure 3, there is shown a device 300 in accordance with embodiments disclosed herein. From the bottom up, device 300 includes anode 310, a hole injection layer 320, a hole transport layer 330, an emissive layer 340, a hole blocking layer 350, an electron transport layer 360, an electron injection layer 370, and a cathode 380.

[0043] In accordance with embodiments disclosed herein, the synergistic combination of materials comprise emissive layer 340, a combination of host material benzo-fused thiophene and phosphorescent dopant and electron transport layer 360. In embodiments, hole blocking layer (HBL) 350 comprising a hole blocking material may be incorporated between emissive layer 340 and electron transport layer 360 to confine excitons within emissive. To perform this role, the HBL material should have HOMO and LUMO energy levels suitable to block hole transport from the emissive layer (EML) to the electron transport layer (ETL) and to pass electrons from the ETL to the EML. In embodiments, the HBL material may be selected from known HBL materials, for example, *BAIq* which is a well-known electron transporting blocking layer material. In embodiments, the material in hole blocking layer 350 may comprise the same benzo-fused thiophene compound that is used as a host material in emissive layer 340.

[0044] The layered structures illustrated in Figures 1, 2 and 3 are provided by way of non-limiting example, and it is understood that embodiments disclosed herein may be used in connection with a wide variety of other structures. The specific materials and structures described are exemplary in nature, and other materials and structures may be used.

Functional OLEDs may be achieved by combining the various layers described in different ways, or layers may be omitted entirely, based on design, performance, and cost factors. Other layers not specifically described may also be included. Materials other than those specifically described may be used. Although many of the examples provided herein describe various layers as comprising a single material, it is understood that combinations of materials, such as a mixture of host and dopant, or more generally a mixture, may be used. Also, the layers may have various sublayers. The names given to the various layers herein are not intended to be strictly limiting. For example, in devices 100 and 300, hole transport layers 130 and 330 transport holes and inject holes into emissive layers 140 and 340, and may be described as hole transport layers or hole injection layers.

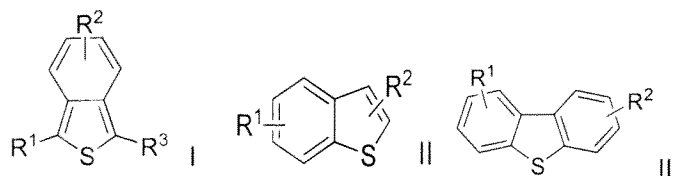
[0045] Unless otherwise specified, any of the layers of the various embodiments may be deposited by any suitable method. For organic layers, methods may include thermal evaporation, ink-jet deposition, such as described in U.S. Pat. Nos. 6,013,982 and 6,087,196, which are incorporated by reference in their entireties, organic vapor phase deposition (OVPD), such as described in U.S. Pat. No. 6,337,102, which is incorporated by reference in its entirety, and deposition by organic vapor jet printing (OVJP), such as described in U.S. Pat. No. 7,431,968, which is incorporated by reference in its entirety. Other suitable deposition methods include spin coating and other solution based processes. Solution based processes may be carried out under nitrogen or other inert atmosphere. For the other layers, methods may include thermal evaporation. In embodiments, patterning methods include deposition through a mask, cold welding such as described in U.S. Pat. Nos. 6,294,398 and 6,468,819, which are incorporated by reference in their entireties, and patterning associated with some of the deposition methods such as ink-jet and OVJD. Other methods may also be used. The materials to be deposited may be modified to make them compatible with a particular deposition method. For example, substituents such as alkyl and aryl groups, branched or unbranched, and typically containing at least 3 carbons, may be used in small molecules to enhance their ability to undergo solution processing. Substituents having up to 20 carbons or more may be used, and thus a range from about 3 to about 20 carbons may be typical. Materials with asymmetric structures may have better solution processability than those having symmetric structures, because asymmetric materials may have a lower tendency to recrystallize. Dendrimer substituents may be used to enhance the ability of small molecules to undergo solution processing.

[0046] Devices fabricated in accordance with embodiments disclosed herein may be incorporated into a wide variety of consumer products, including flat panel displays, computer monitors, televisions, billboards, lights for interior or exterior illumination and/or signaling, heads up displays, fully transparent displays, flexible displays, laser printers, telephones, cell phones, personal digital assistants (PDAs), laptop computers, digital cameras, camcorders, viewfinders, micro-displays, 3-D displays, vehicles, a large area wall, theater or stadium

screen, or a sign. Various control mechanisms may be used to control devices fabricated in accordance with the present embodiments, including passive matrix and active matrix. Many of the devices are intended for use in a temperature range comfortable to humans, such as 18 degrees C to 30 degrees C, and those close to "room temperature" (*i.e.*, about 20 to 25 degrees C), but could be used outside this temperature range, for example, from -40 degree C to +80 degree C.

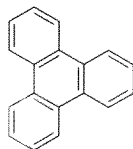
[0047] The materials and structures described herein may have applications in devices other than OLEDs. For example, other optoelectronic devices such as organic solar cells and organic photodetectors may employ the materials and structures disclosed herein. More generally, organic devices, such as organic transistors, may also employ the materials and structures disclosed herein.

[0048] Returning now to Figure 3, in embodiments, host material of emissive layer 340 comprise the benzo-fused thiophene comprises a compound of Formula I, Formula II or Formula III:



wherein R¹, R² and R³ are independently selected from the group consisting of alkyl, alkoxy, amino, alkenyl, alkynyl, arylalkyl, aryl, aralkyl, heteroaryl, and hydrogen.

[0049] In embodiments, compounds of Formula I, II and III may comprise at least one aryl group that is a triphenylene group:



triphenylene

[0050] Triphenylene is a polyaromatic hydrocarbon with high triplet energy, yet high pi-conjugation and a relatively small energy difference between the first singlet and first triplet levels. Thus, triphenylene has relatively accessible HOMO and LUMO levels compared to other aromatic compounds with similar triplet energy such as biphenyl. Triphenylene can readily accommodate red, green and even blue phosphorescent dopants to give high efficiency without energy quenching. Benzo-fused thiophenes may be used as hole transporting organic conductors. In addition, the triplet energies of benzothiophenes of Formula I II are relatively high. A combination of benzo-fused thiophenes and triphenylene as hosts in PHOLED may be particularly beneficial. Benzo-fused thiophenes are typically more hole transporting than electron transporting, and triphenylene is more electron transporting than hole transporting. Therefore, combining these two moieties in one molecule may offer

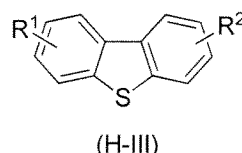
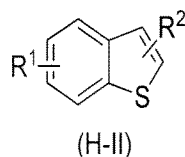
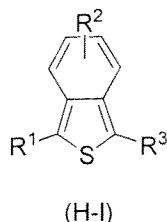
improved charge balance which may improve device performance in terms of lifetime, efficiency and low voltage. Different chemical linking motifs of the two moieties can be used to tune the properties of the resulting compound to match a particular phosphorescent emitter, device architecture, and / or fabrication process. For example, *m*-phenylene linkage may
5 provide higher triplet energy and higher solubility relative to *p*-phenylene.

[0051] Compounds of Formula I, II and III may be substituted with groups that are not necessarily triphenylenes. In embodiments, any group that is used as a substituent of Formula I may be selected with a triplet energy high enough to maintain the benefit of having
10 triphenylene benzo-fused thiophenes. Examples of such groups that may be used as substituents of Formula I, II and III may include a substituent selected from the group consisting of C_nH_{2n+1} , OC_nH_{2n+1} , OAr_1 , $N(Ar_1)(Ar_2)$, $CH=CH-C_nH_{2n+1}$, $C=CHC_nH_{2n+1}$, Ar_1 , Ar_1-Ar_2 , $C_nH_{2n}-Ar_1$, or no substitution, wherein *n* is 1, 2, 3, 4, 5, 6, 7, 8, 9, or 10, and wherein Ar_1 and Ar_2 are independently selected from the group consisting of benzene, biphenyl, naphthalene,
15 triphenylene, carbazole, and heteroaromatic analogs thereof. The compounds described herein may have a sufficiently high triplet energy to be suitable for use in a device having phosphorescent blue emissive materials.

[0052] The substituents of the compounds described herein are generally unfused such that the substituents are not fused to the triphenylene, benzo-fused furan or benzo-fused
20 thiophene moieties of the compound. However, the substituents may optionally be inter-fused (*i.e.* fused to each other).

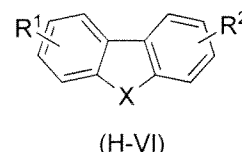
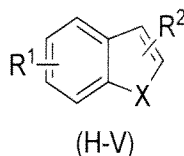
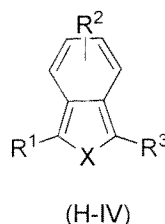
[0053] Similar to the characterization of benzo-fused thiophenes, benzo-fused furans are also typically hole transporting materials having relatively high triplet energy. Examples of benzo-fused furans include benzofuran and dibenzofuran. Therefore, a material containing
25 both triphenylene and benzofuran may be advantageously used as host or hole blocking material in PHOLED. A compound containing both of these two groups may offer improved electron stabilization which may improve device stability and efficiency with low voltage. The properties of the triphenylene containing benzofuran compounds may be tuned as necessary by using different chemical linkages to link the triphenylene and the benzofuran.

30 **[0054]** Examples of triphenylene-containing benzo-fused thiophenes useful in the devices disclosed herein include compounds having the structure of the following formulae (H-I), (H-II) and (H-III)



[0055] Where R^1, R^2 and R^3 are independently selected from alkyl, alkoxy, amino, alkenyl, alkynyl, arylkyl, aryl, heteroaryl and hydrogen. Each of R^1, R^2 and R^3 may represent multiple substituents. At least one of R^1, R^2 and R^3 in Formula (H-I) and at least one of R^1 and R^2 in Formulas (H-II) and (H-III) includes a triphenylene group. The triphenylene group may be linked directly to the structure of formulae (H-I), (H-II) or (H-III), but there may also be a "spacer" in between the triphenylene group and the structure of formulae (H-I), (H-II) or (H-III).

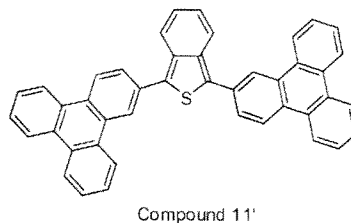
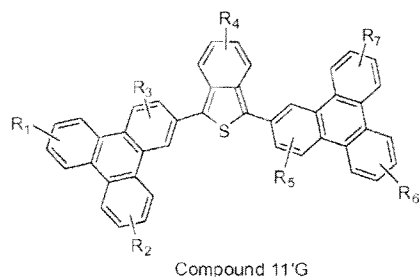
[0056] Examples of triphenylene-containing benzo-fused thiophenes or benzo-fused furans include compounds having the structure of the following formulae (H-IV), (H-V), and (H-VI):



where X is S or O and wherein R^1, R^2 and R^3 are unfused substituents that are independently selected from C_nH_{2n+1} , OC_nH_{2n+1} , OAr_1 , $N(C_nH_{2n+1})_2$, $N(Ar_1)(Ar_2)$, $CH=CH-C_nH_{2n+1}$, $C=CHC_nH_{2n+1}$, Ar_1 , Ar_1-Ar_2 , $C_nH_{2n}-Ar_1$, or no substitution. Each of R^1, R^2 and R^3 may represent mono, di, tri, or tetra substitutions, n is 1, 2, 3, 4, 5, 6, 7, 8, 9, or 10. Ar_1 and Ar_2 are independently selected from the group consisting of benzene, biphenyl, naphthalene, triphenylene, carbazole, and heteroaromatic analogs thereof. At least one of R^1, R^2 and R^3 in Formula (H-IV) and at least one of R^1 and R^2 in Formulas (H-V) and (H-VI) includes a triphenylene group.

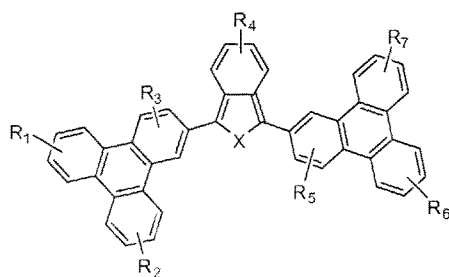
[0057] .

[0058] Examples of compounds having the structure of the formula (H-I) include:

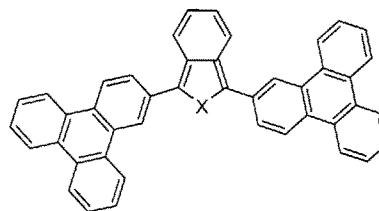


R_1 to R_7 represents, independently, mono, di, tri or tetra substitutions selected from alkyl, alkoxy, amino, alkenyl, alkynyl, arylkyl, aryl and heteroaryl, or no substitution.

[0059] Examples of compounds having the structure of the formula (H-IV) include:



Compound 11G

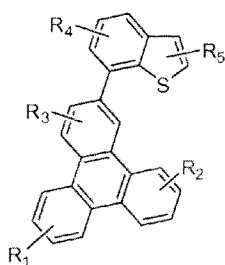


Compound 11

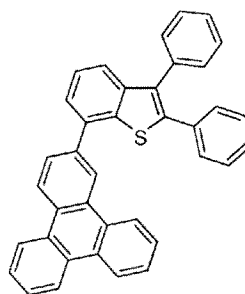
wherein R_3 , R_4 , R_5 , R_6 , and R_7 , at each occurrence, are selected independently from the group consisting of C_nH_{2n+1} , OC_nH_{2n+1} , OAr_1 , $N(C_nH_{2n+1})_2$, $N(Ar_1)(Ar_2)$, $CH=CH-C_nH_{2n+1}$,

- 5 $C\equiv CHC_nH_{2n+1}$, Ar_1 , Ar_1-Ar_2 , $C_nH_{2n}-Ar_1$, and no substitution, wherein n is 1, 2, 3, 4, 5, 6, 7, 8, 9, or 10, and wherein Ar_1 and Ar_2 are independently selected from the group consisting of benzene, biphenyl, naphthalene, triphenylene, carbazole, and heteroaromatic analogs thereof.

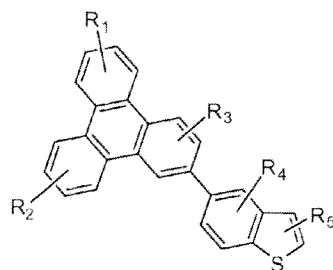
[0060] Examples of compounds having the structure of the formula (H-II) include:



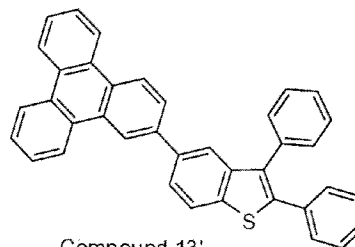
Compound 12'G



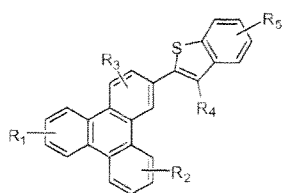
Compound 12'



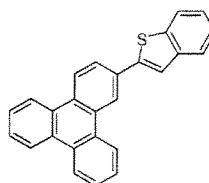
Compound 13'G



Compound 13'

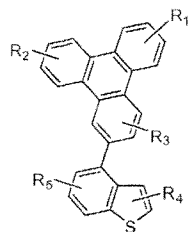


Compound 14'G

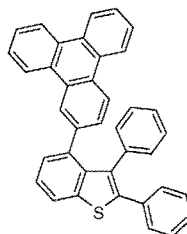


Compound 14'

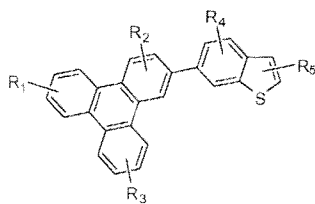
14



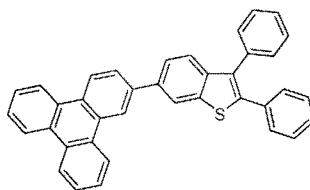
Compound 16'G



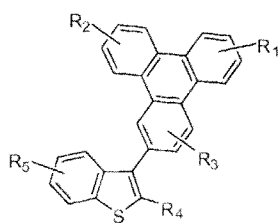
Compound 16'



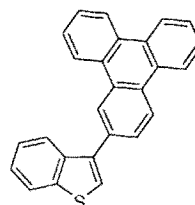
Compound 17'G



Compound 17'



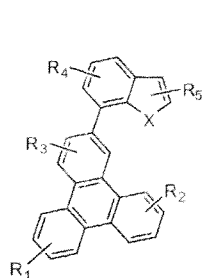
Compound 18'G



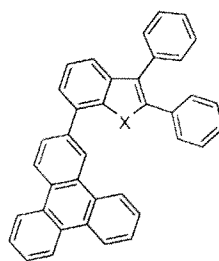
Compound 18'

where R_1 to R_5 represent, independently, mono, di, tri or tetra substitutions selected from alkyl, alkoxy, amino, alkenyl, alkynyl, arylkyl, aryl and heteroaryl, or no substitution.

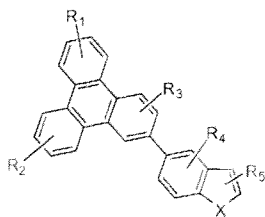
[0061] Examples of compounds having the structure of the formula (H-V) include:



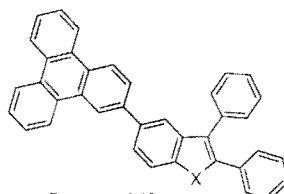
Compound 12G



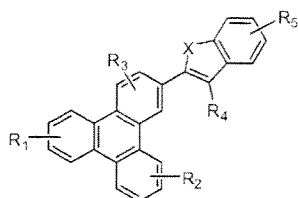
Compound 12



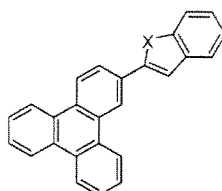
Compound 13G



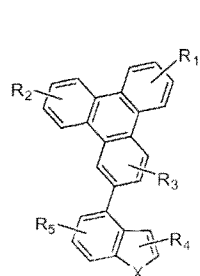
Compound 13



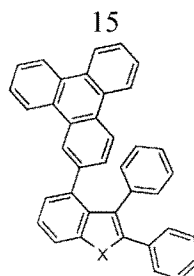
Compound 14G



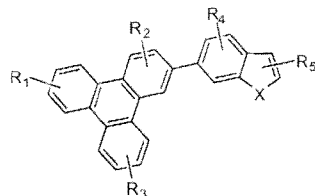
Compound 14



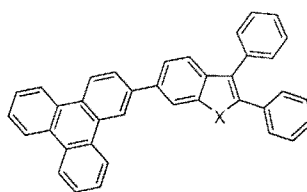
Compound 16G



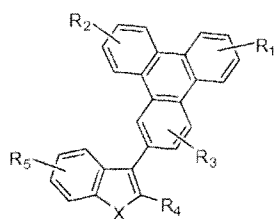
Compound 16



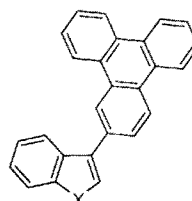
Compound 17G



Compound 17



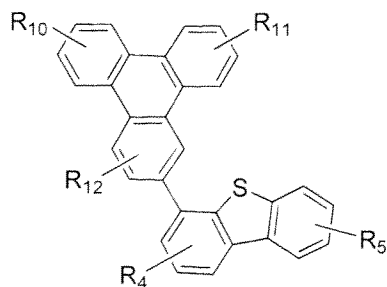
Compound 18G



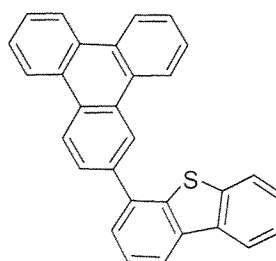
Compound 18

where X is S or O. In some embodiments, X is S. R_1 to R_5 are independently selected from the group consisting of C_nH_{2n+1} , OC_nH_{2n+1} , OAr_1 , $N(C_nH_{2n+1})_2$, $N(Ar_1)(Ar_2)$, $CH=CH-C_nH_{2n+1}$, $C=CHC_nH_{2n+1}$, Ar_1 , Ar_1-Ar_2 , $C_nH_{2n}-Ar_1$, or no substitution. Each of R_1 to R_5 may represent mono, di, tri, or tetra substitutions., n is 1, 2, 3, 4, 5, 6, 7, 8, 9, or 10. Ar_1 and Ar_2 are independently selected from the group consisting of benzene, biphenyl, naphthalene, triphenylene, carbazole, and heteroaromatic analogs thereof.

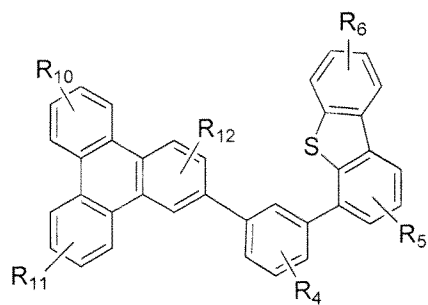
10 [0062] Examples of compounds having the structure of Formula (H-III) include: .



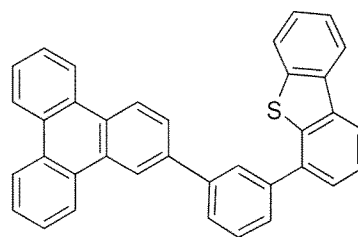
Compound 1'G



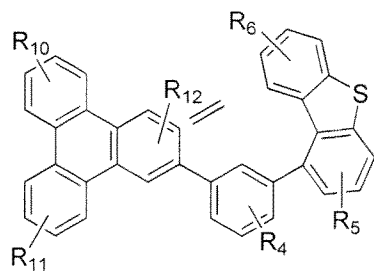
Compound 1'



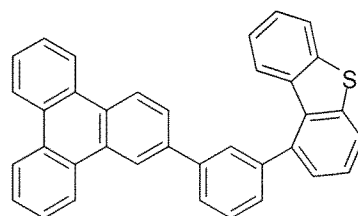
Compound 2'G



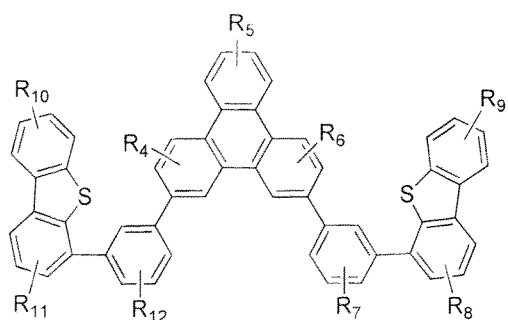
Compound 2'



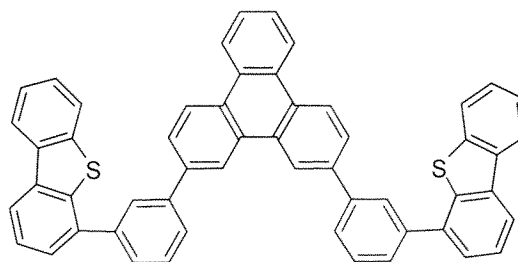
Compound 3'G



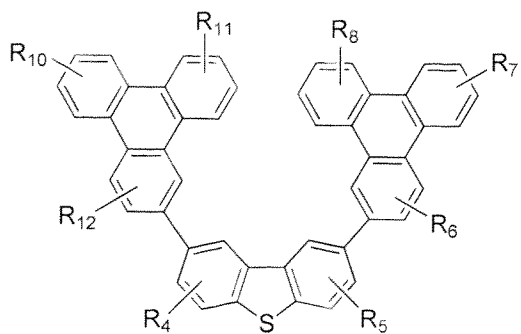
Compound 3'



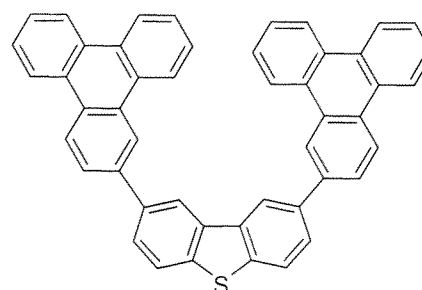
Compound 4G



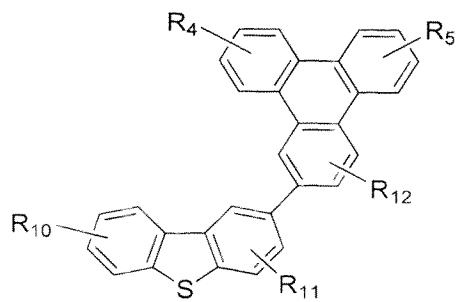
Compound 4



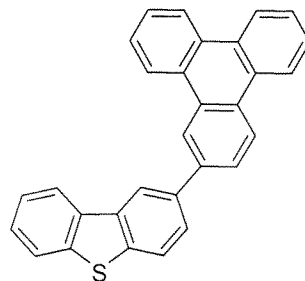
Compound 5'G



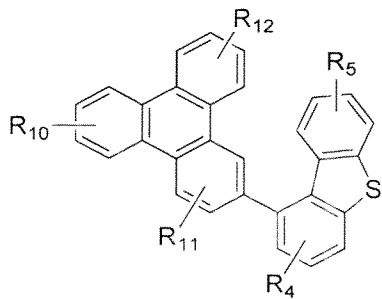
Compound 5'



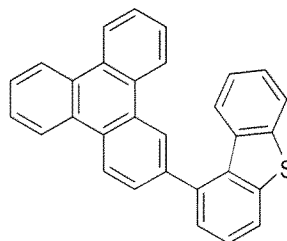
Compound 6'G



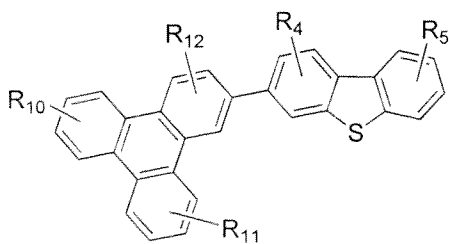
Compound 6'



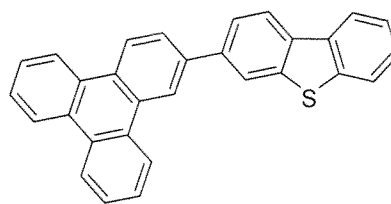
Compound 7'G



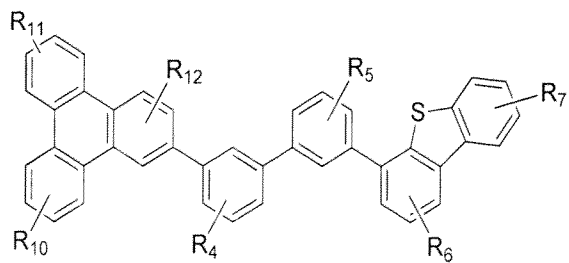
Compound 7'



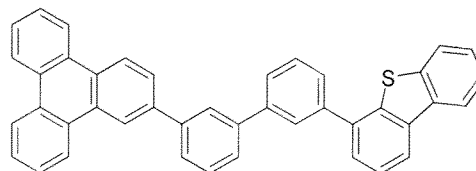
Compound 8'G



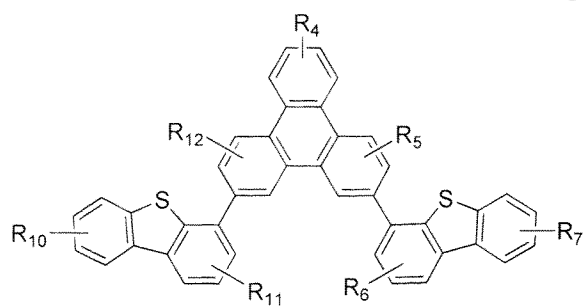
Compound 8'



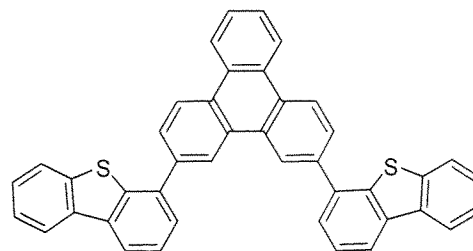
Compound 9'G



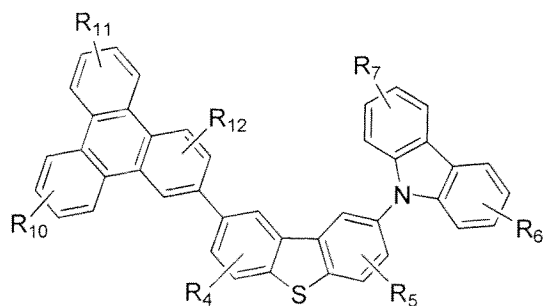
Compound 9'



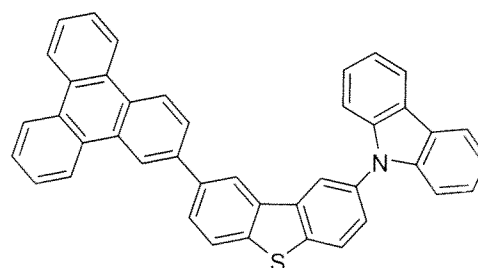
Compound 10'G



Compound 10'



Compound 15'G

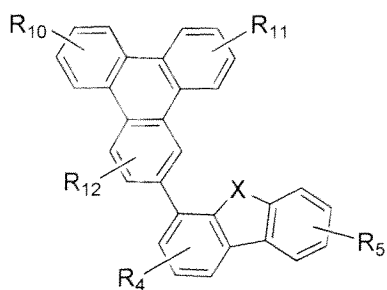


Compound 15'

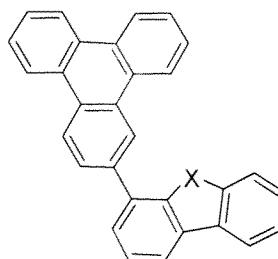
where R₄, R₅, R₆, R₇, R₁₀, R₁₁ and R₁₂ represent, independently, mono, di, tri or tetra
substitutions selected from alkyl, alkoxy, amino, alkenyl, alkynyl, arylkyl, aryl and heteroaryl,
5 or no substitution(H).

[0063]

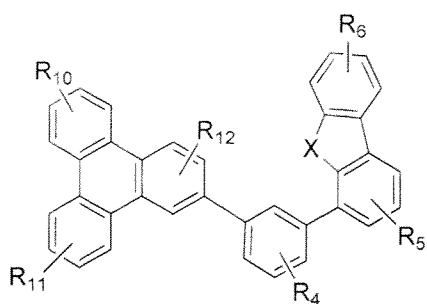
Examples of compounds having the formula (H-VI) include



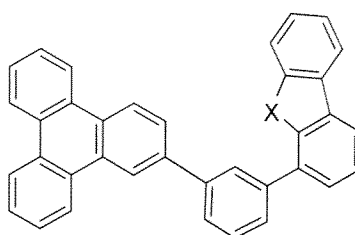
Compound 1G



Compound 1

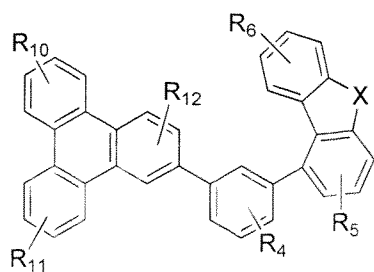


Compound 2G

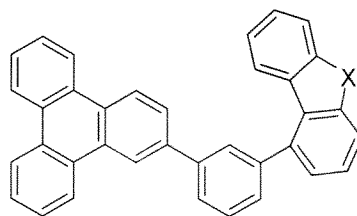


Compound 2

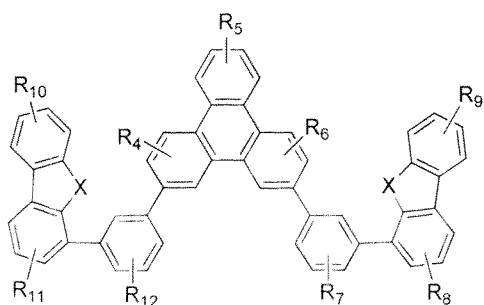
19



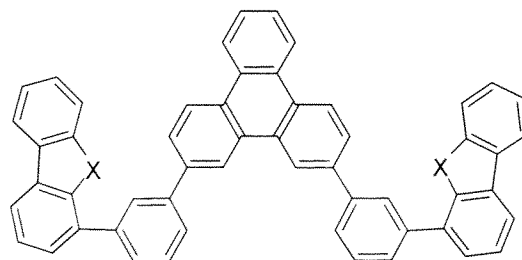
Compound 3G



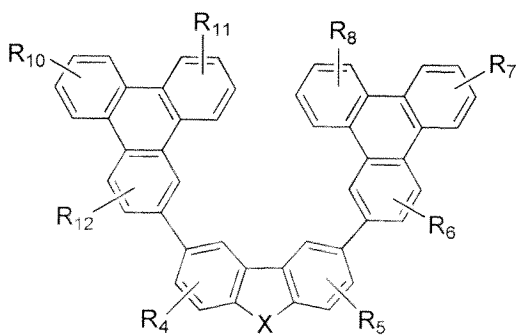
Compound 3



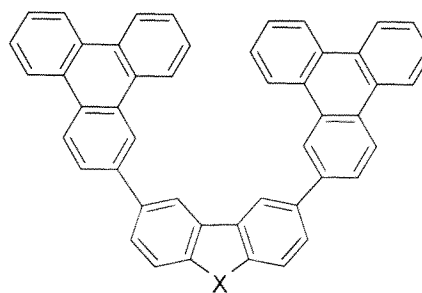
Compound 4G



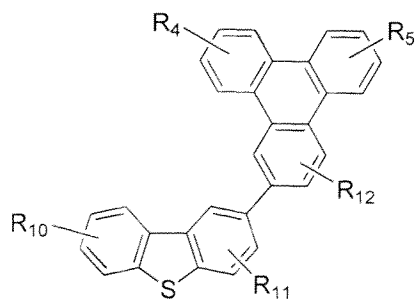
Compound 4



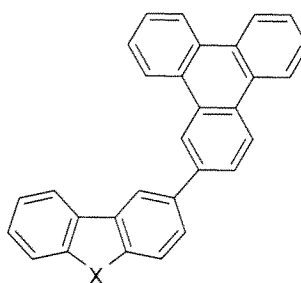
Compound 5G



Compound 5

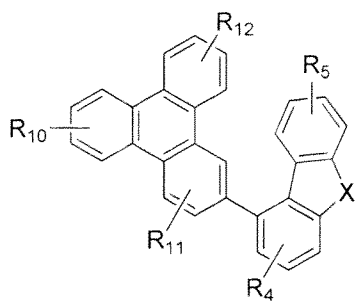


Compound 6G

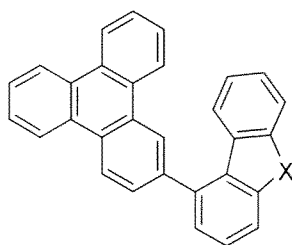


Compound 6

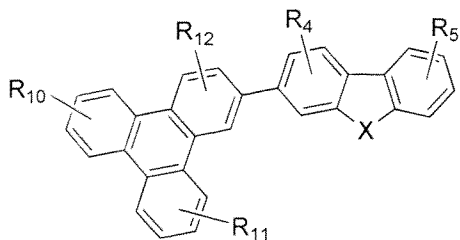
20



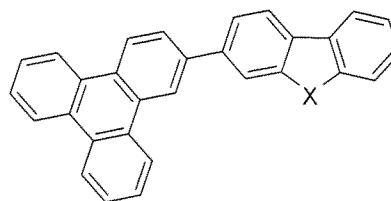
Compound 7G



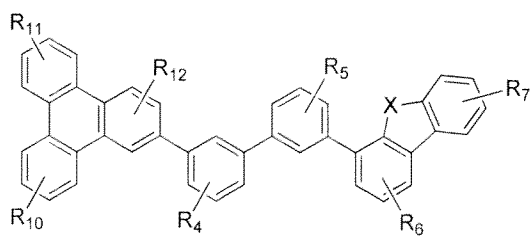
Compound 7



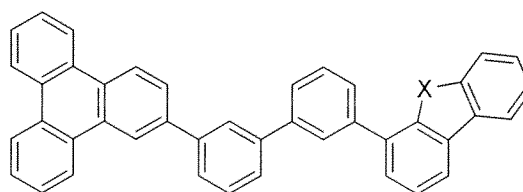
Compound 8G



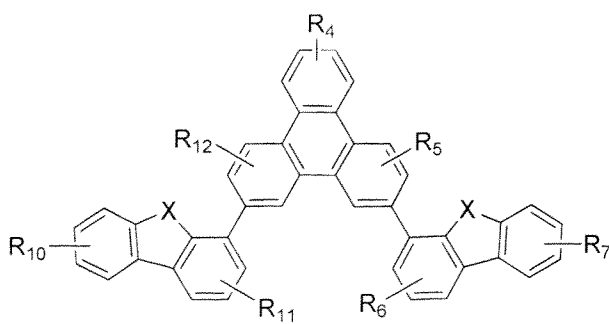
Compound 8



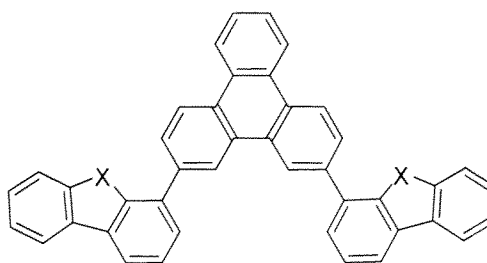
Compound 9G



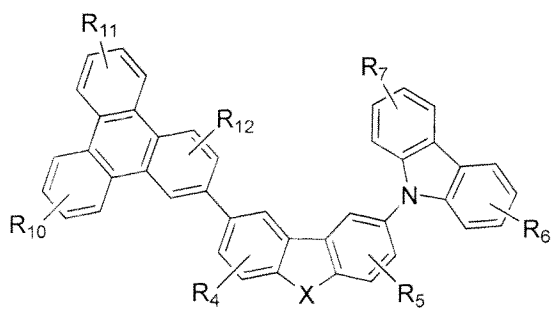
Compound 9



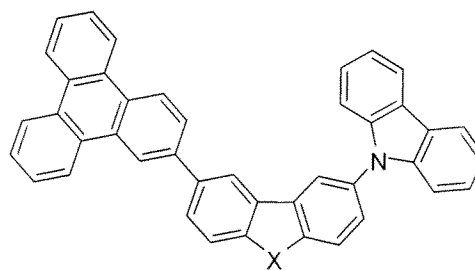
Compound 10G



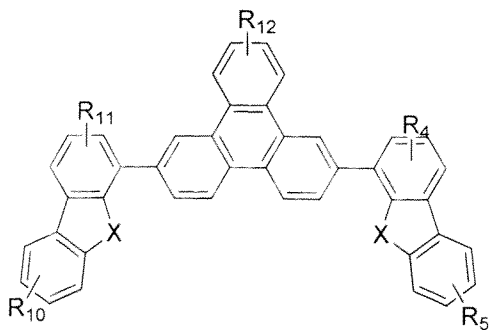
Compound 10



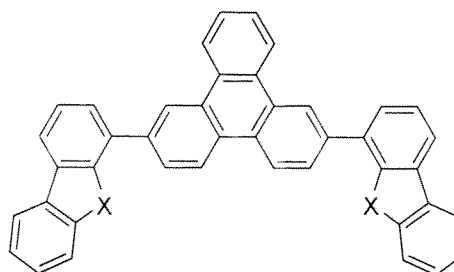
Compound 15G



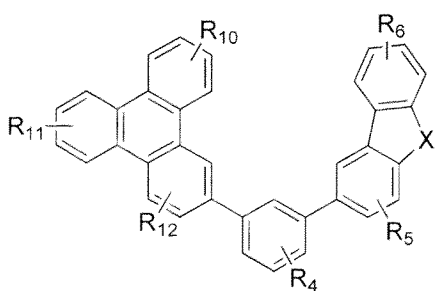
Compound 15



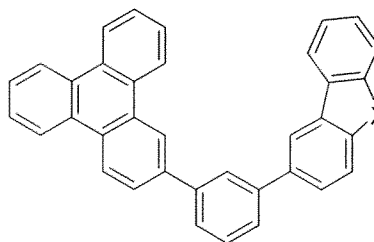
Compound 19 G



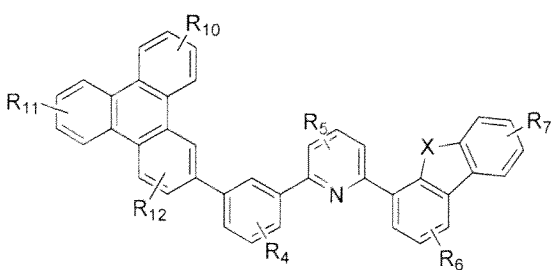
Compound 19



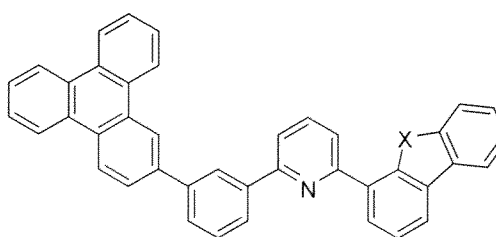
Compound 20 G



Compound 20

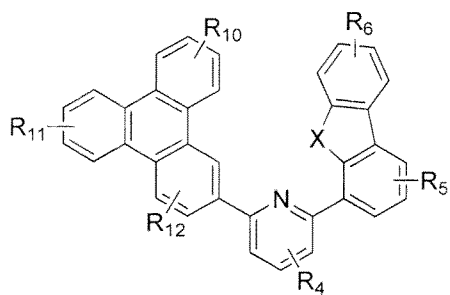


Compound 21 G

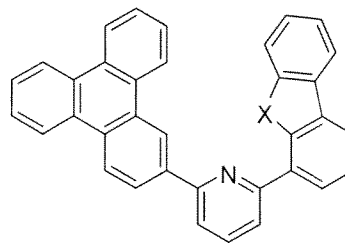


Compound 21

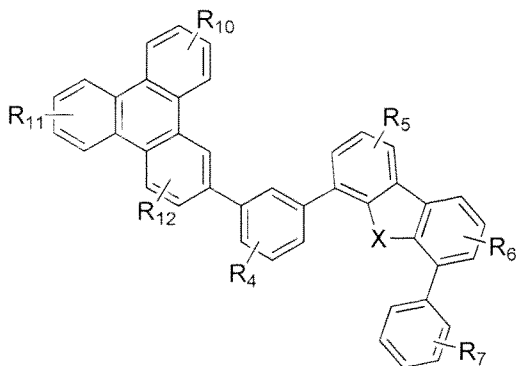
22



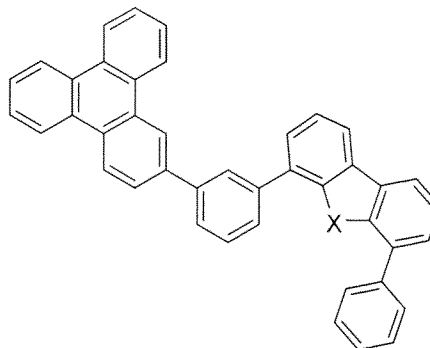
Compound 22 G



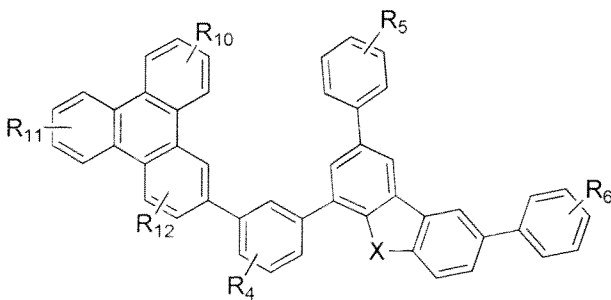
Compound 22



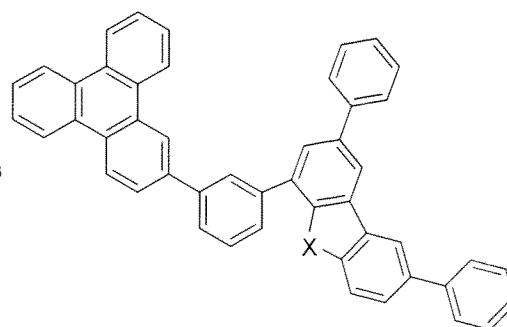
Compound 23 G



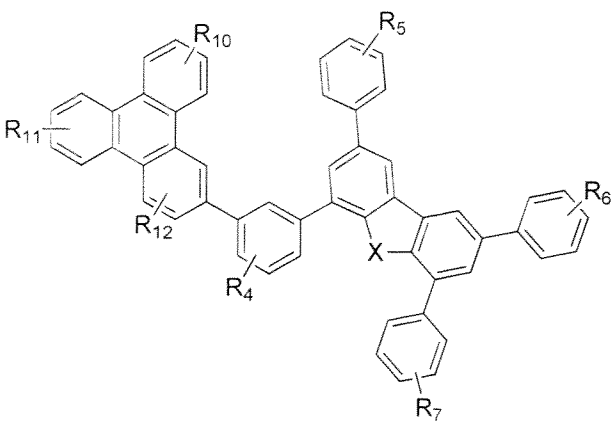
Compound 23



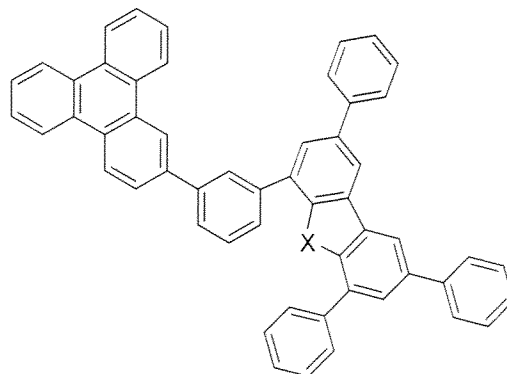
Compound 24 G



Compound 24

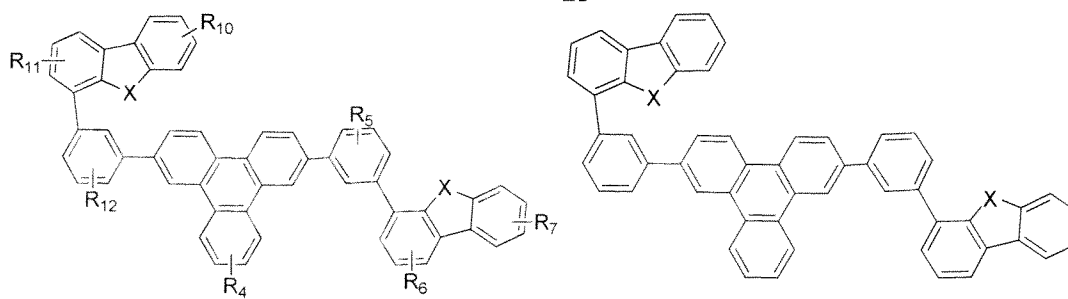


Compound 25 G



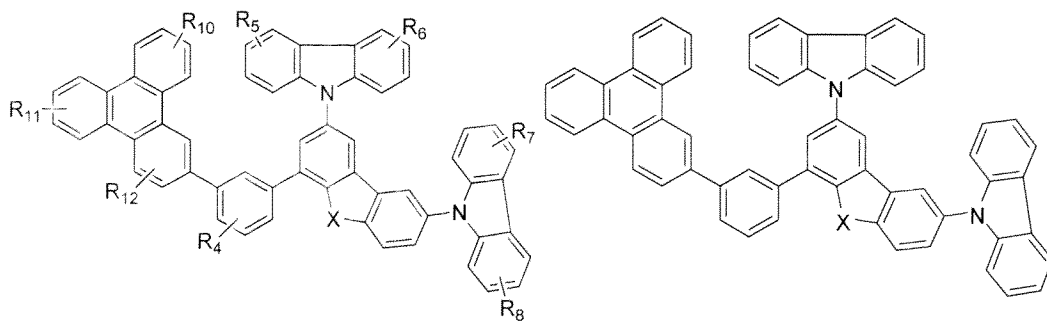
Compound 25

23



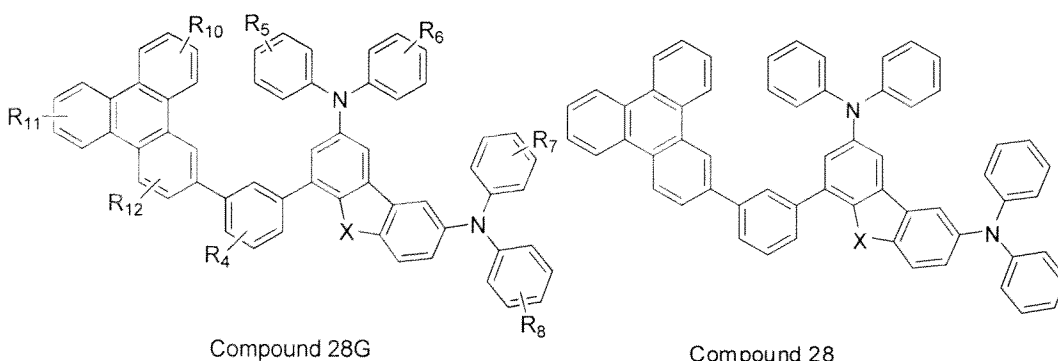
Compound 26G

Compound 26



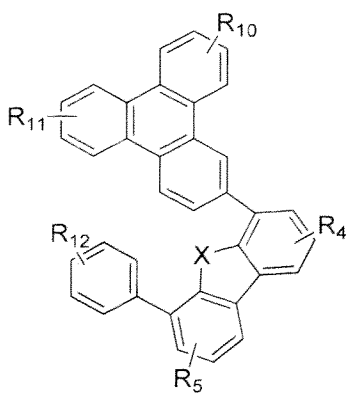
Compound 27G

Compound 27

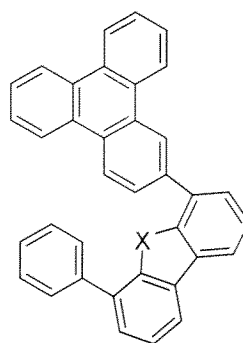


Compound 28G

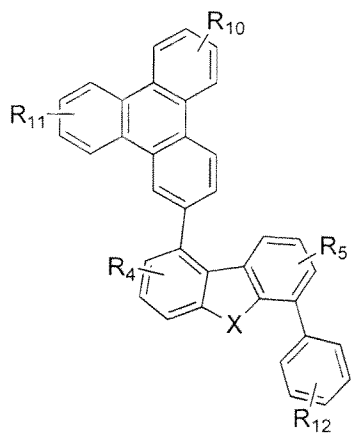
Compound 28



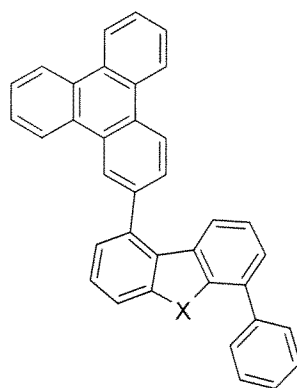
Compound 29G



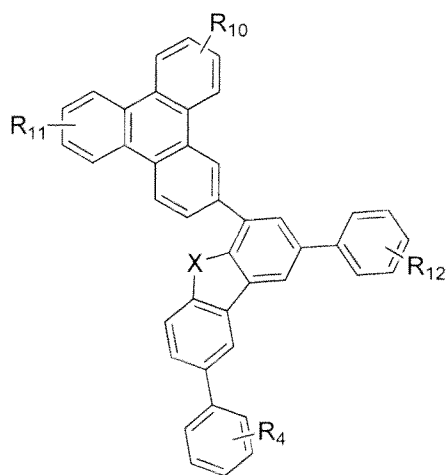
Compound 29



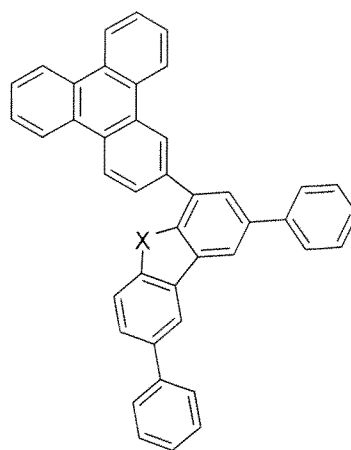
Compound 30G



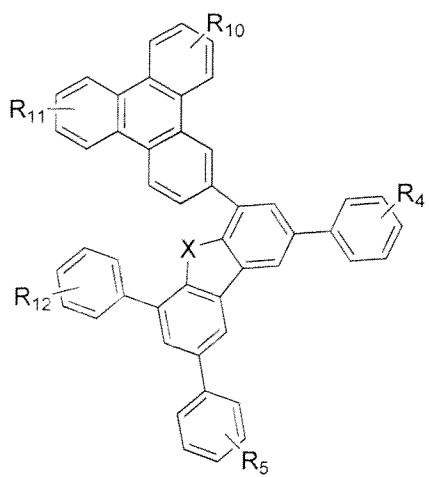
Compound 30



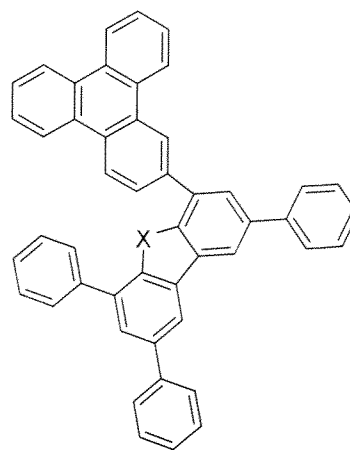
Compound 31G



Compound 31

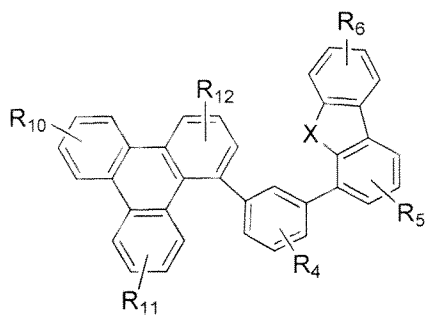


Compound 32G

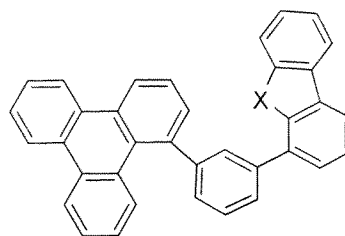


Compound 32

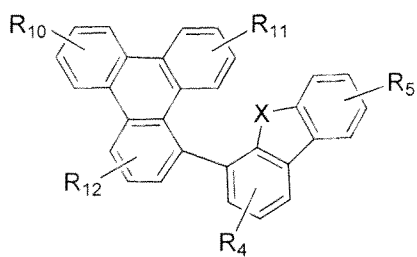
25



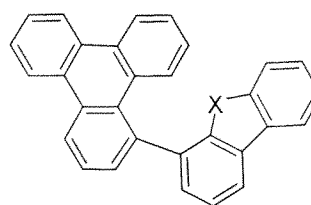
Compound 33G



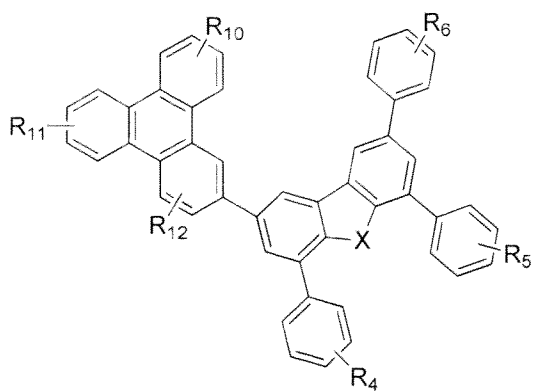
Compound 33



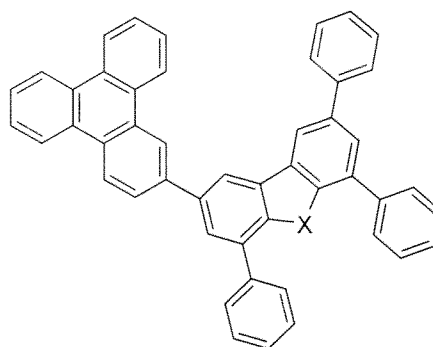
Compound 34G



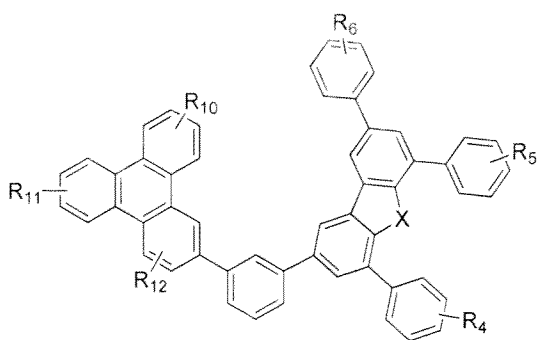
Compound 34



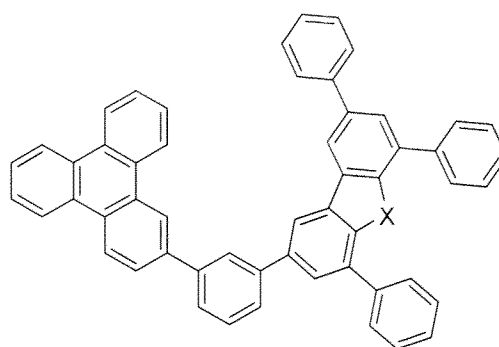
Compound 35G



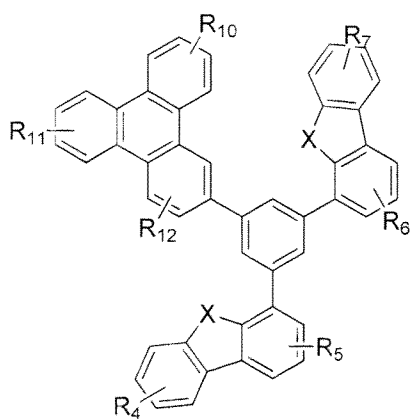
Compound 35



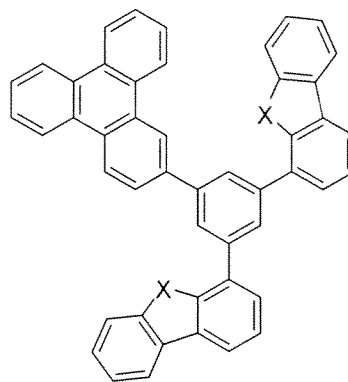
Compound 36G



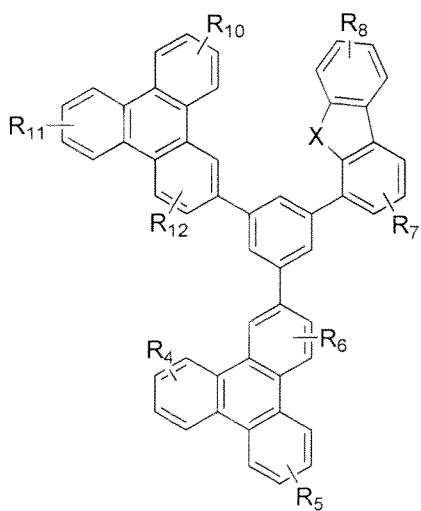
Compound 36



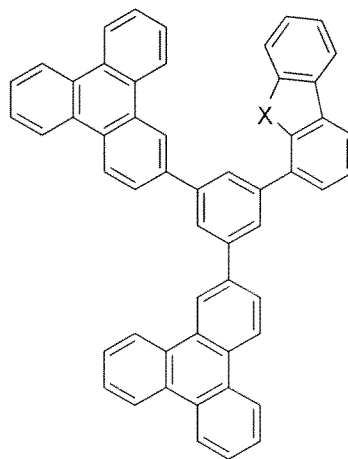
Compound 37G



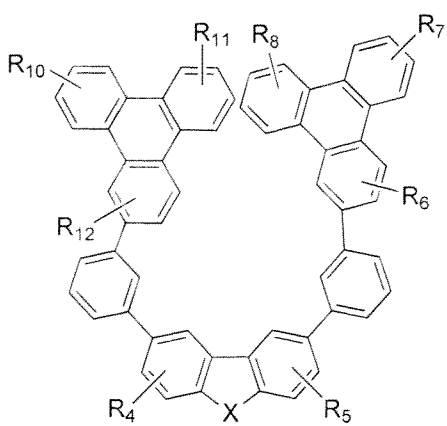
Compound 37



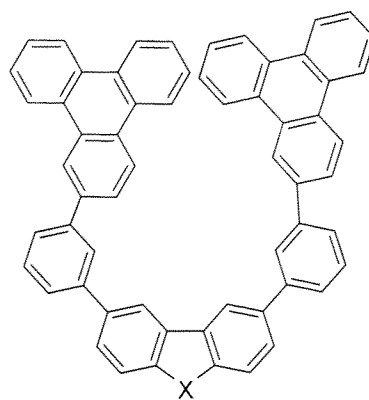
Compound 38G



Compound 38

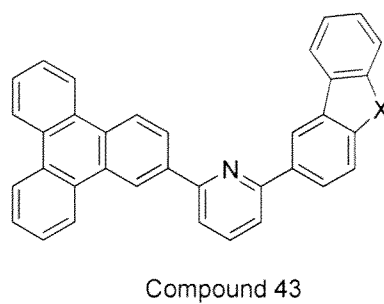
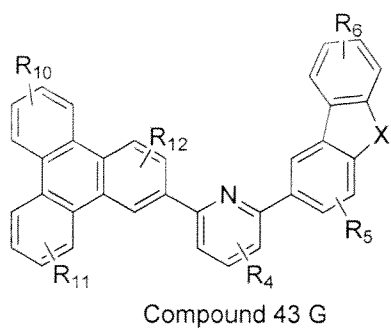
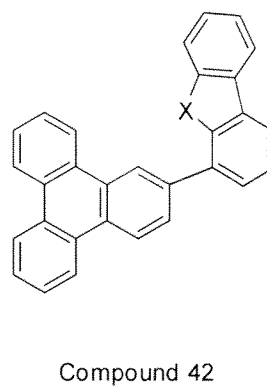
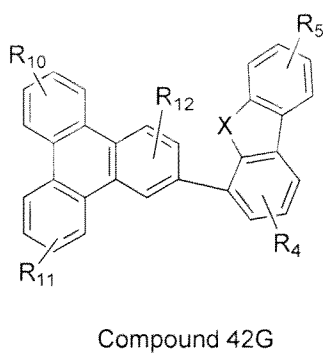
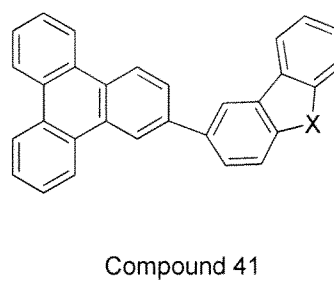
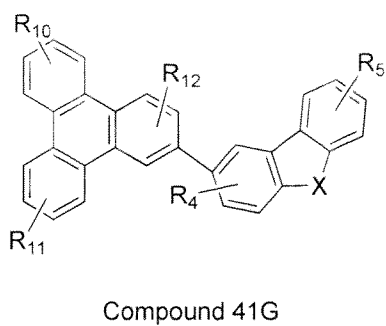
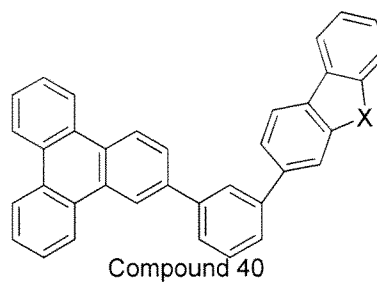
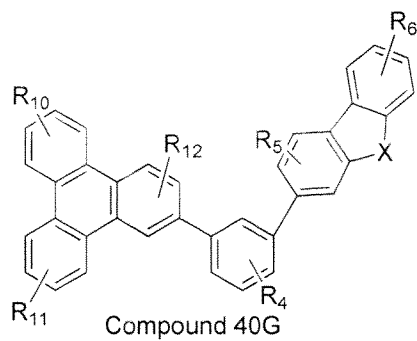


Compound 39G

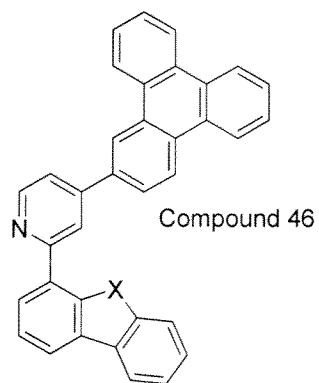
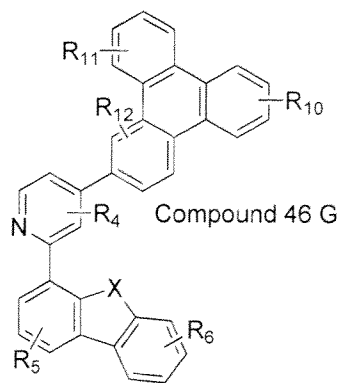
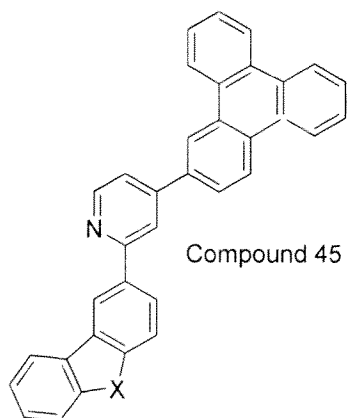
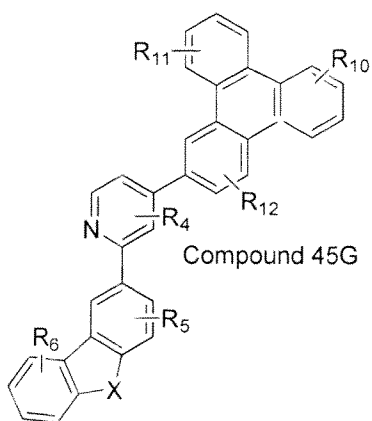
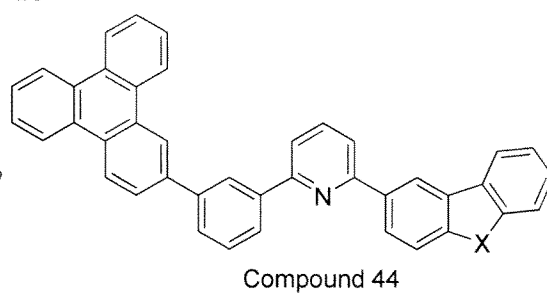
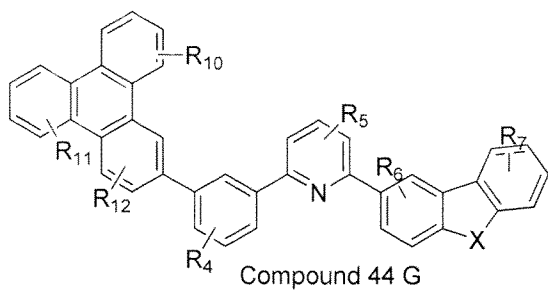


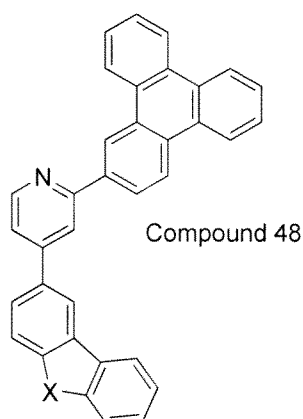
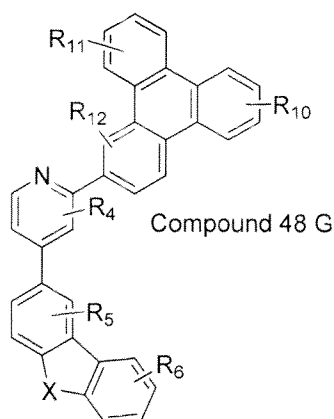
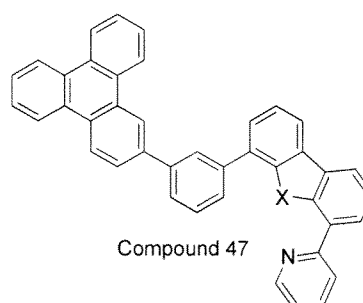
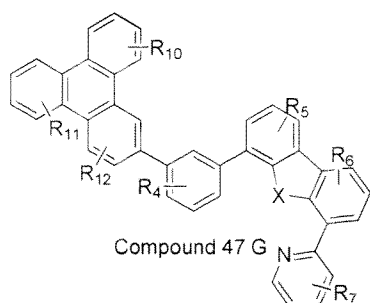
Compound 39

27



28

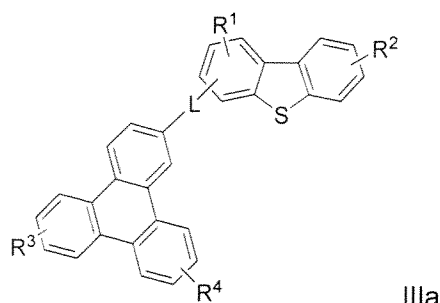




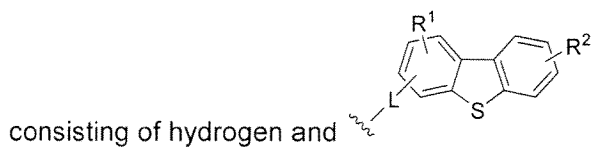
where X is S or O. In some embodiments, X is S, wherein R_4 , R_5 , R_6 , R_7 , R_8 , R_9 , R_{10} , R_{11} and R_{12} are independently selected from the group consisting of C_nH_{2n+1} , OC_nH_{2n+1} , OAr_1 , $N(C_nH_{2n+1})_2$, $N(Ar_1)(Ar_2)$, $CH=CH-C_nH_{2n+1}$, $C=CHC_nH_{2n+1}$, Ar_1 , Ar_1-Ar_2 , $C_nH_{2n}-Ar_1$, or no substitution. Each of R_1 to R_n may represent mono, di, tri, or tetra substitutions. n is 1, 2, 3, 4, 5, 6, 7, 8, 9, or 10. Ar_1 and Ar_2 are independently selected from the group consisting of benzene, biphenyl, naphthalene, triphenylene, carbazole, and heteroaromatic analogs thereof.

[0064] In embodiments, the present disclosure comprises an OLED which comprises a benzo-fused thiophene host material, wherein the triplet energy of the host material is from about 2.0 eV to about 2.8 eV.

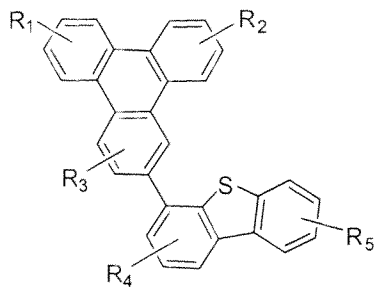
[0065] In embodiments, the benzo-fused thiophene comprises a compound of Formula Ia:



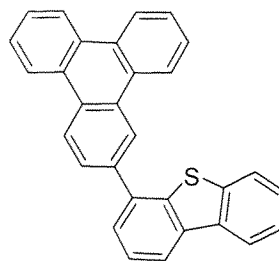
wherein each R^1 and R^2 are independently selected from the group consisting of alkyl, alkoxy, amino, alkenyl, alkynyl, arylalkyl, aryl, aralkyl, heteroaryl, and hydrogen; L is bond or an optionally substituted phenyl group; and R^3 and R^4 are independently selected from the group



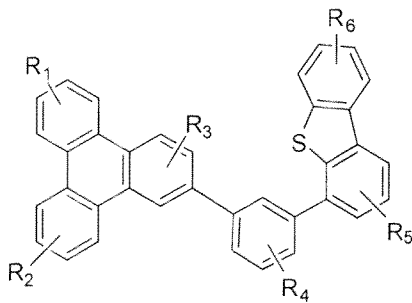
- 5 [0066] Examples of compounds of Formula III or IIIa include the following: Examples of compounds having the structure of Formula(H-III) include: .



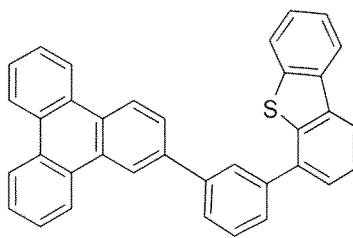
Compound 1'G



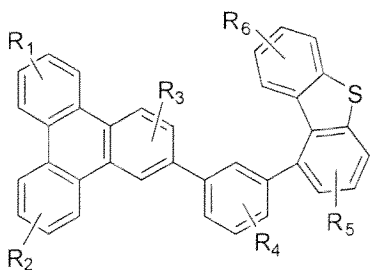
Compound 1'



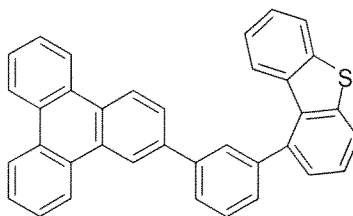
Compound 2'G



Compound 2'

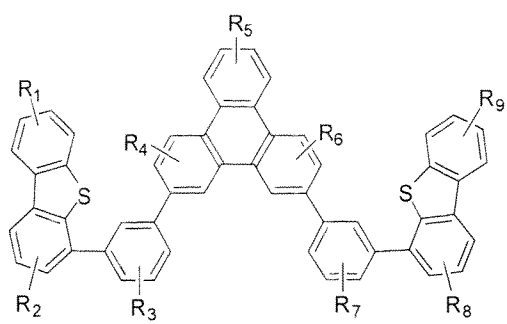


Compound 3'G

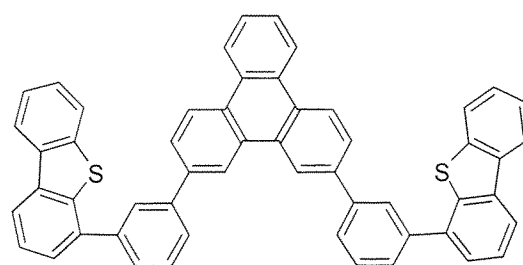


Compound 3'

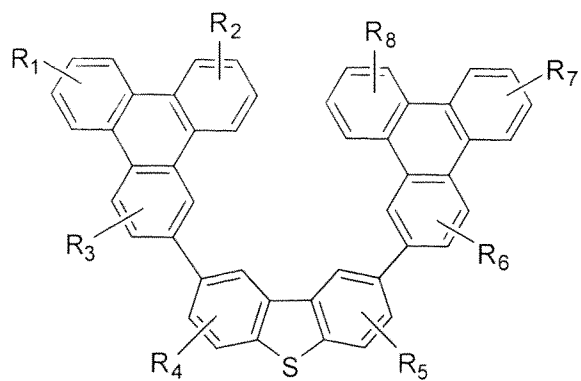
31



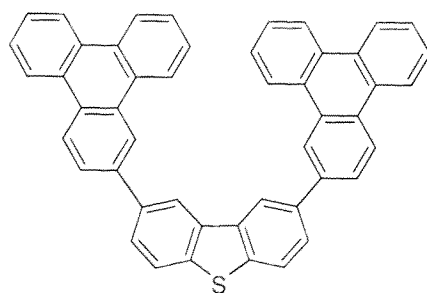
Compound 4G



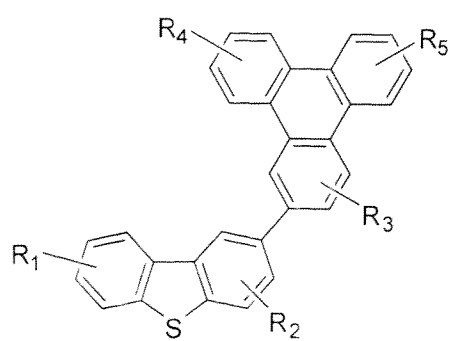
Compound 4



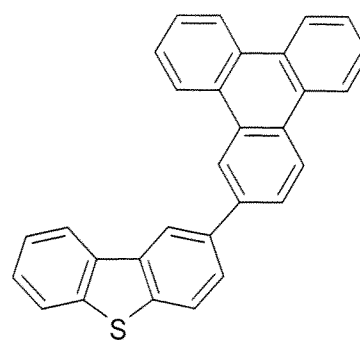
Compound 5'G



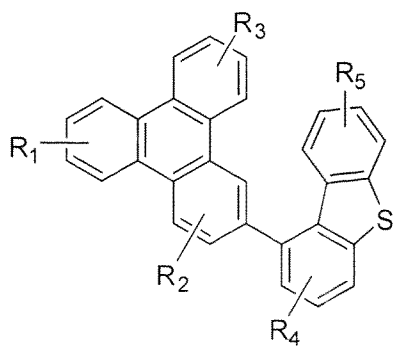
Compound 5'



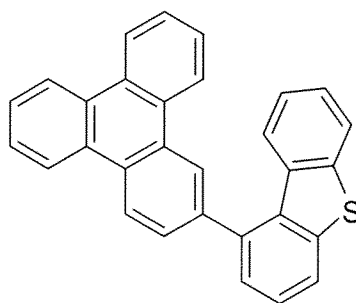
Compound 6'G



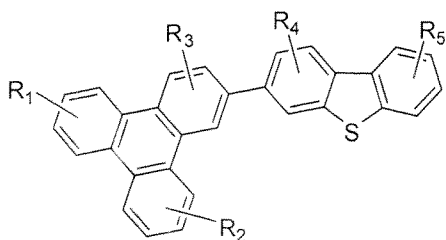
Compound 6'



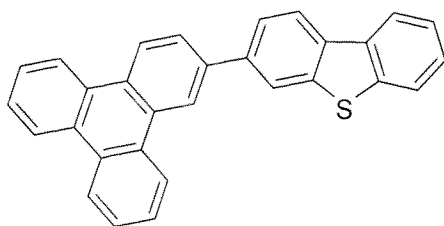
Compound 7'G



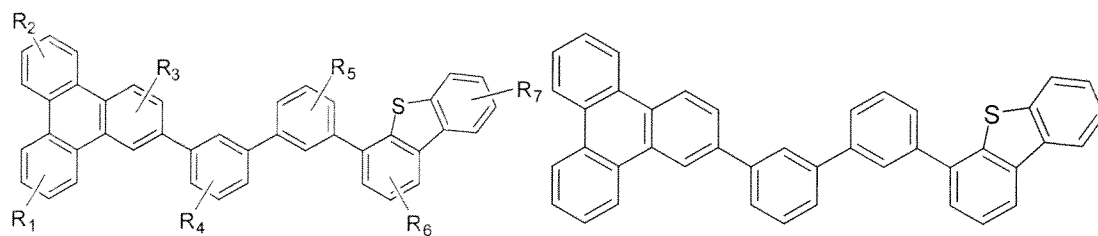
Compound 7'



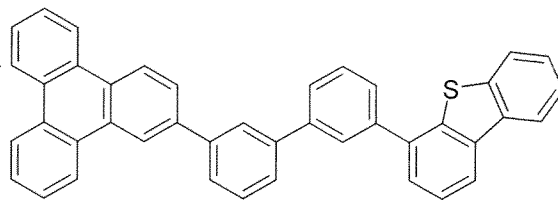
Compound 8'G



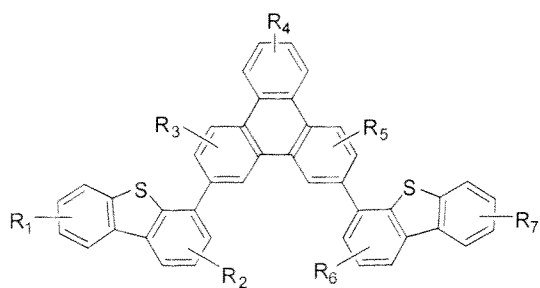
Compound 8'



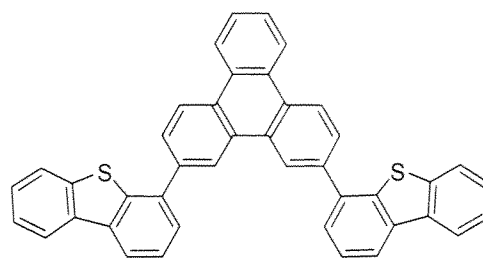
Compound 9'G



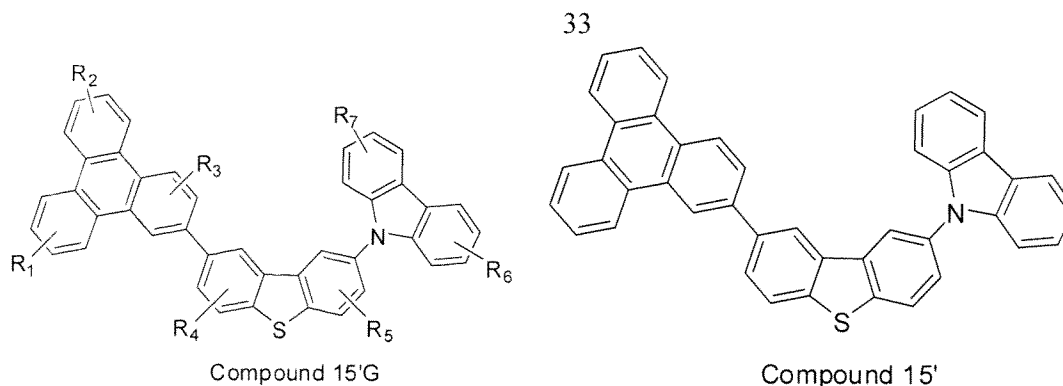
Compound 9'



Compound 10'G

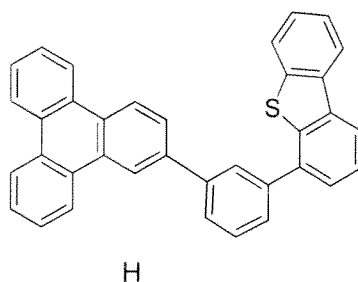


Compound 10'



where R₁ to R₇ represents, independently, mono, di, tri or tetra substitutions selected from alkyl, alkoxy, amino, alkenyl, alkynyl, arylkyl, aryl and heteroaryl, or no substitution (*i.e.*, hydrogen).

- 5 **[0067]** In embodiments, the benzofused thiophene host is Compound 2' (hereinafter Compound "H"):



- 10 In embodiments, the host material and hole blocking material are the same, *i.e.*, both are triphenylene containing benzo-fused thiophenes. That is, in embodiments, the host material of the emissive layer and the hole blocking material of the hole blocking layer may be the same. In some such embodiments, the host material and the hole blocking material comprise compound H. The preparation of compounds of Formula I, II and III, including
- 15 Compound H (previously disclosed as Compound 2'), are disclosed in U.S. Pat. Application Publication No. 2011/084599 (WO 2009/021126) which is incorporated herein by reference in its entirety.

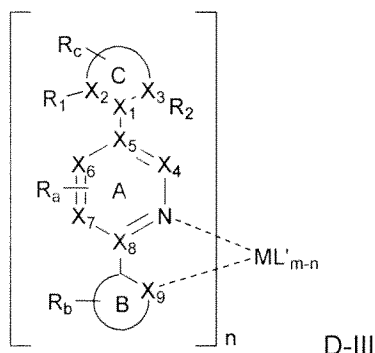
- [0068]** In embodiments, emissive layer 340 has a thickness from about 100 to about 600 angstroms or about 200 angstroms to about 400 angstroms, or about 250 to about 350
- 20 angstroms, or about 280 to about 320 angstroms. In embodiments, hole blocking layer 150, which may comprise the same host material as the emissive layer, has a thickness from about 10 to about 100 angstroms, or about 25 to about 75 angstroms, or about 35 to about 65 angstroms, or about 45 to about 55 angstroms.

- [0069]** Some examples of the phosphorescent emitter material doped into emissive
- 25 layer 340 are heteroleptic phosphorescent organometallic compounds represented by the formula L₂MX, LL'MX, LL'L''M, or LMXX', wherein L, L', L'', X, and X' are inequivalent,

bidentate ligands and M is a metal that forms octahedral complexes, wherein L, L', and L'' are monoanionic inequivalent bidentate ligands coordinated to M through an sp^2 hybridized carbon and a heteroatom.

[0070] The phosphorescent organometallic compound may be a compound selected from the group consisting of phosphorescent organometallic platinum compounds, organometallic iridium compounds and organometallic osmium compounds. The organometallic platinum compounds, iridium compounds and osmium compounds can each include an aromatic ligand.

[0071] In embodiments, the phosphorescent dopant present in emissive layer 340 comprises a heteroleptic transition metal complex comprising a compound of Formula D-III:

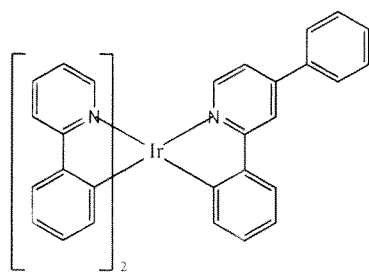


wherein B and C are each independently a 5 or 6-membered carbocyclic or heterocyclic rings; wherein A-B is a bonded pair of carbocyclic or heterocyclic rings coordinated to a metal M via a nitrogen atom in ring A and an sp^2 hybridized atom in ring B; wherein A-C is a bonded pair of carbocyclic or heterocyclic rings; wherein each R_a , R_b , and R_c are independently mono, di, tri, or tetra substitutions and each R_a , R_b , and R_c are independently selected from the group consisting of hydrogen, alkyl, alkoxy, amino, alkenyl, alkynyl, arylkyl, aryl, and heteroaryl, any of which may be optionally substituted; wherein X_1 , X_2 , X_3 , X_4 , X_5 , X_6 , X_7 , X_8 , and X_9 are independently selected from carbon and nitrogen; wherein R_1 and R_2 are independently selected from the group consisting of hydrogen, alkyl, alkoxy, amino, alkenyl, alkynyl, arylkyl, aryl, and heteroaryl, any of which may be optionally substituted; and wherein at least one of R_1 , R_2 , and the R_a substituents adjacent to C is not hydrogen; wherein M is a coordinated metal having an atomic number greater than 40, m is the oxidation state of the metal, and n is an integer of at least 1.

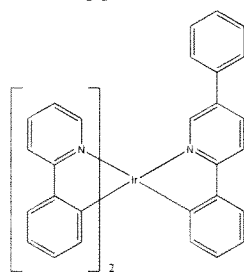
In embodiments, phosphorescent emissive compounds are provided that comprise Ir (III) heteroleptic complexes having extended conjugation on the heterocyclic ring which coordinates to the metal through nitrogen. The compounds provided have the formula selected from the group consisting of:

Heteroleptic iridium compounds are provided, which may be used in organic light emitting devices as the emissive dopant of such devices. The heteroleptic compounds may be selected from the group consisting of:

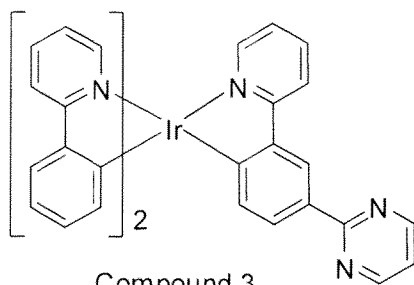
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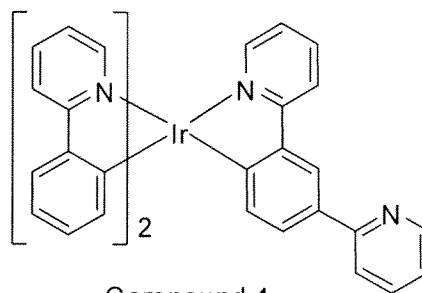
Compound 1



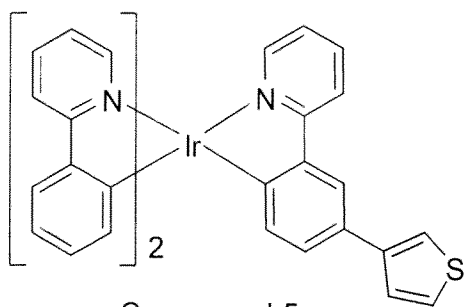
Compound 2



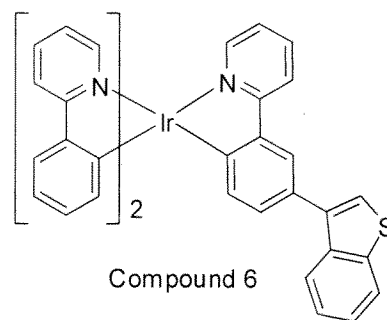
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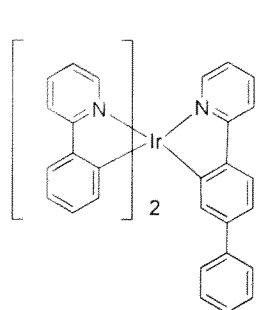
Compound 4



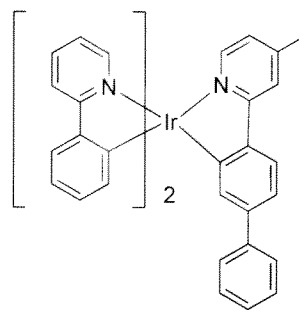
Compound 5



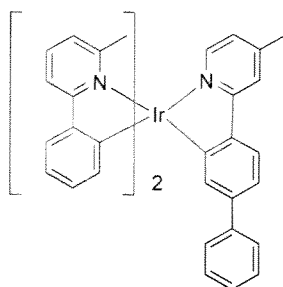
Compound 6



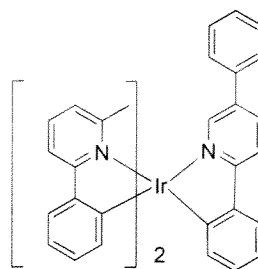
Compound 8



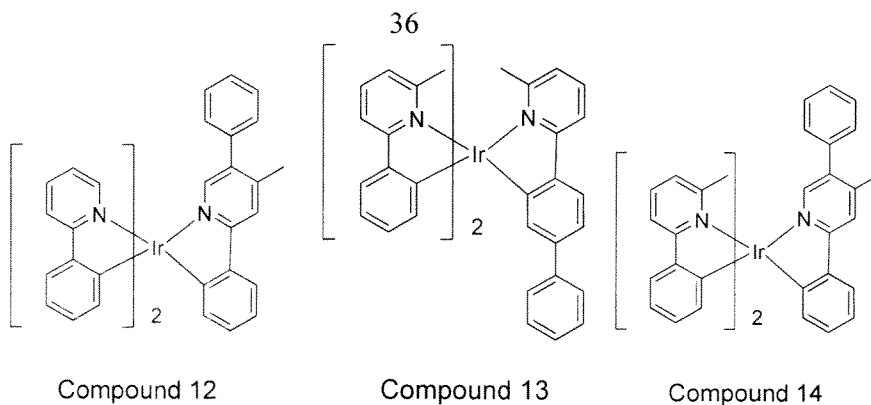
Compound 9



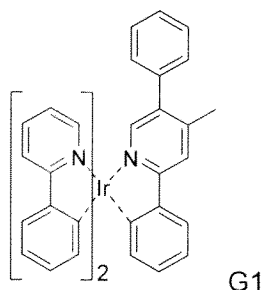
Compound 10



Compound 11

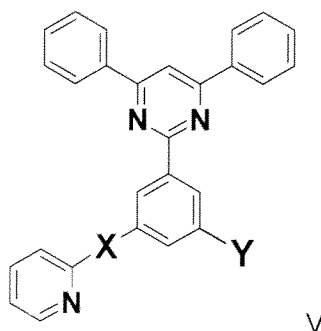


[0072] In embodiments, the heteroleptic transition metal complex is a Compound 12 (hereinafter Compound G1):



- 5 [0073] Methods of preparing such phosphorescent dopants, including compound 12 are disclosed in U.S. Patent Application Publication No. 2011/227049, which is incorporated herein by reference in its entirety. In embodiments, the phosphorescent dopant is present in emissive layer 140 in a range from about .5 to about 30 percent by weight of the layer or about 1 to about 20 percent by weight of the layer or about 5 percent to about 15 percent by weight of the layer.

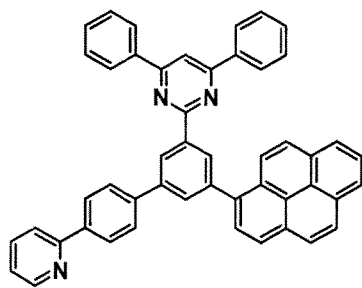
[0074] In embodiments, electron transport layer 360 comprises a compound of Formula V:



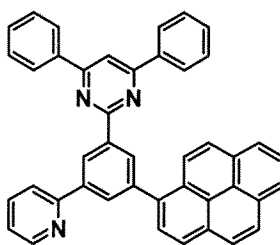
where X represents a single chemical bond or phenylene group, and Y represents anthracenyl group or pyrenyl group. Examples of a phenylene group for X include 1,2-phenylene, 1,3-phenylene and 1,4-phenylene. Examples of anthracenyl group of Y include anthracen-9-yl, anthracen-1-yl and anthracen-2-yl. Examples of pyrenyl group of Y include pyren-1-yl, pyren-2-yl and pyren-4-yl.

[0075] Exemplary compounds of structure V include structures ETL-1, ETL-2, and ETL-3 below:

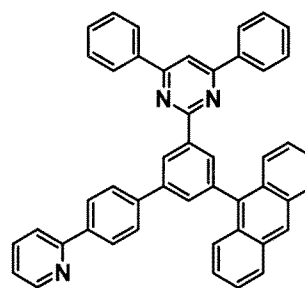
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ETL-1



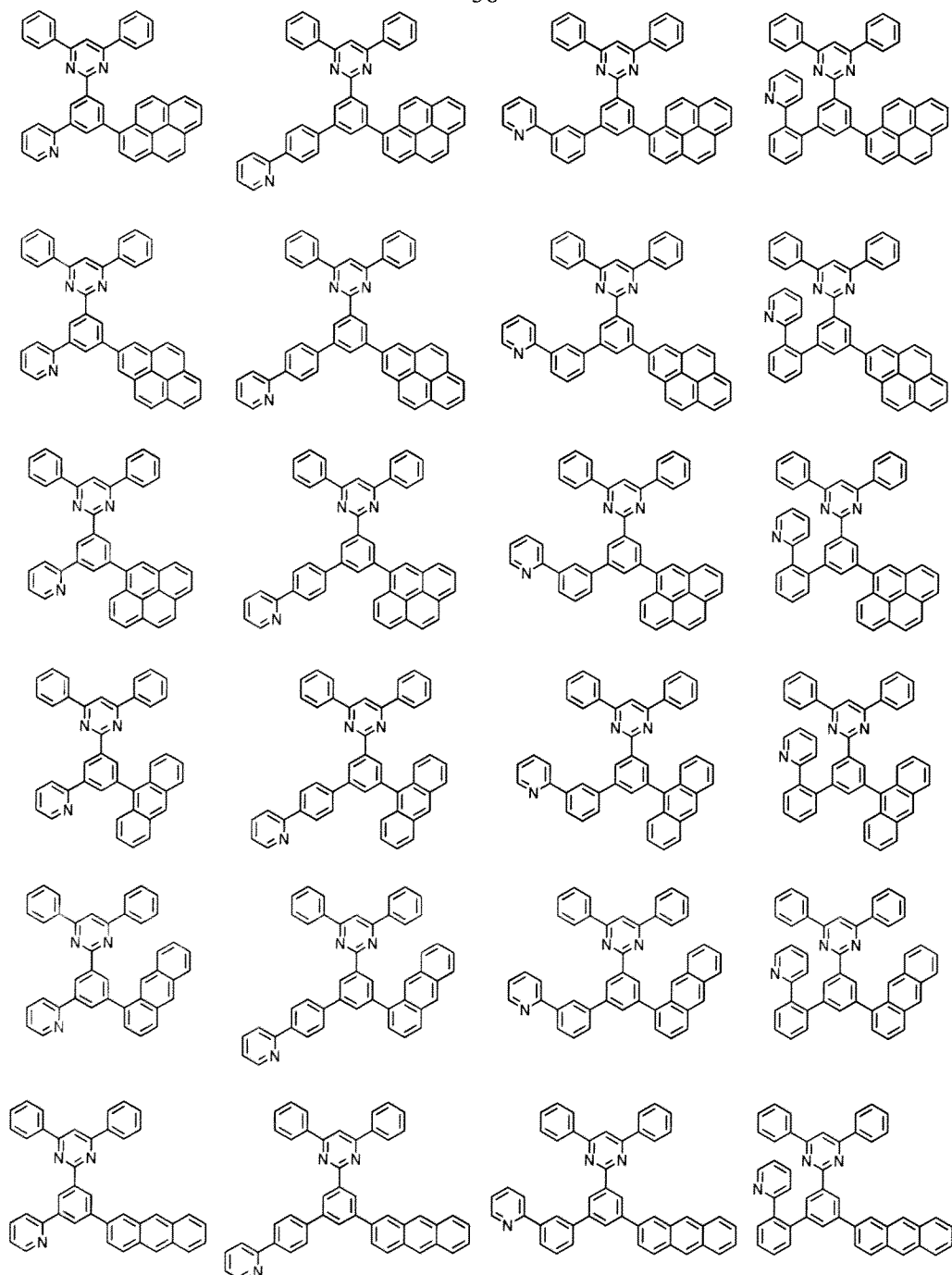
ETL-2



ETL-3

[0076] Further examples of compound 5 are provided below which are described in U.S. Application Publication No. 2012/0214993, which is incorporated herein by reference in its entirety:

5

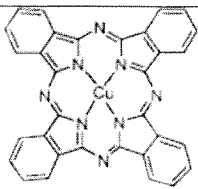
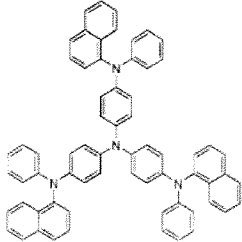
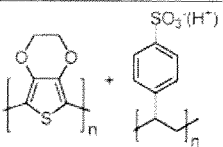
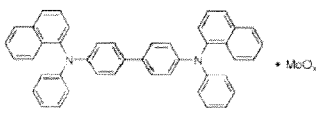
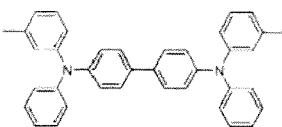
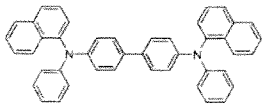


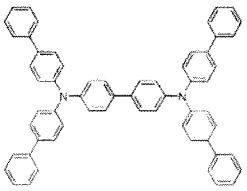
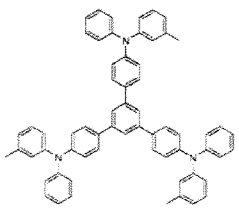
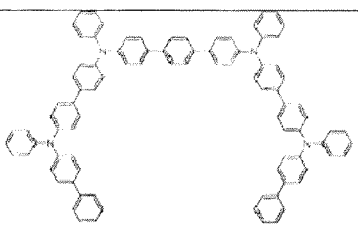
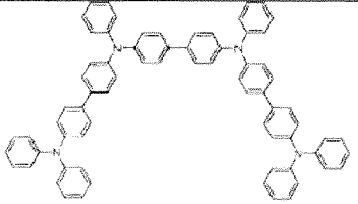
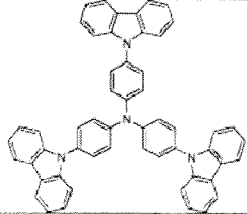
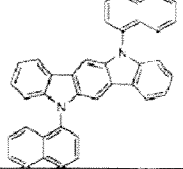
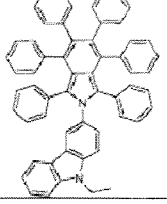
[0077] In embodiments, the electron transport layer has a thickness from about 10 to about 600 angstroms or about 350 angstroms to about 550 angstroms, or about 400 to about 500 angstroms.

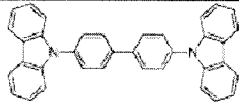
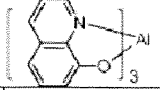
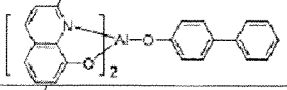
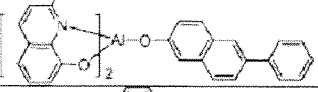
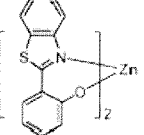
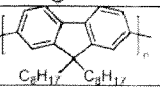
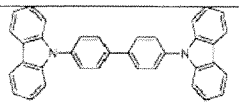
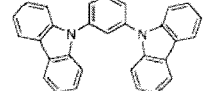
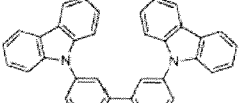
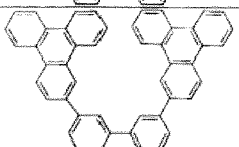
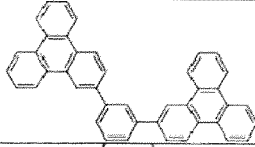
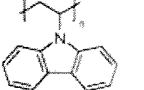
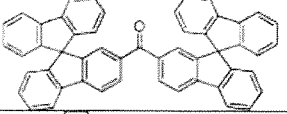
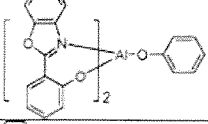
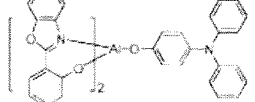
5 **[0078]** The materials described herein as useful for a particular layer in an organic light emitting device may be used in combination with a wide variety of other materials present in the device. For example, emissive dopants disclosed herein may be used in conjunction with a wide variety of hosts, transport layers, blocking layers, injection layers, electrodes and other layers that may be present. The materials described or referred to below are non-limiting
10 examples of materials that may be useful in combination with the compounds disclosed

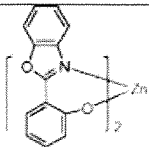
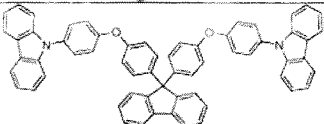
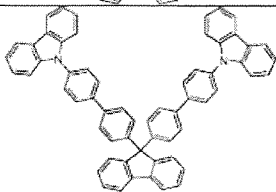
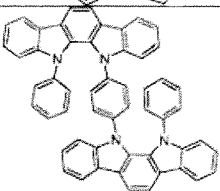
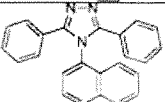
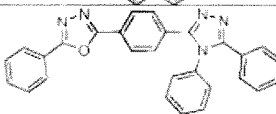
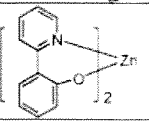
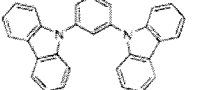
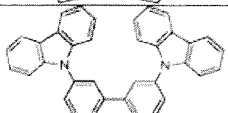
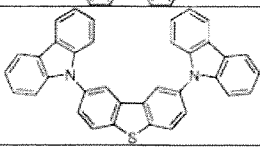
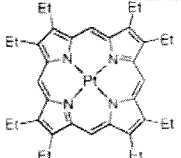
herein, and one of skill in the art can readily consult the literature to identify other materials that may be useful in combination.

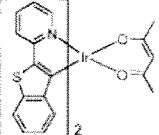
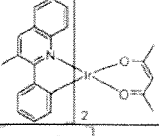
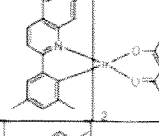
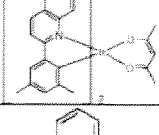
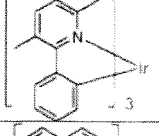
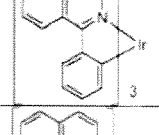
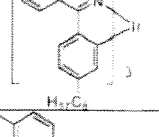
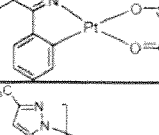
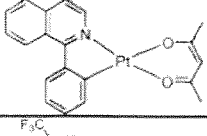
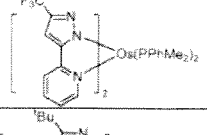
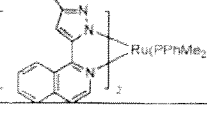
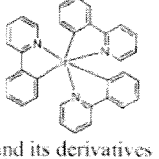
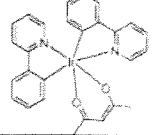
- [0079]** In addition to and/or in combination with the materials disclosed herein, many hole injection materials, hole transporting materials, host materials, dopant materials, exciton/hole blocking layer materials, electron transporting and electron injecting materials may be used in an OLED. Non-limiting examples of the materials that may be used in an OLED in combination with materials disclosed herein are listed in Table 1 below. Table 1 lists non-limiting classes of materials, non-limiting examples of compounds for each class, and references that disclose the materials.

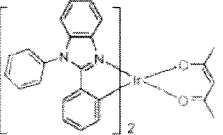
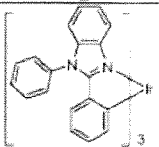
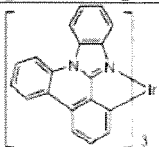
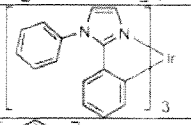
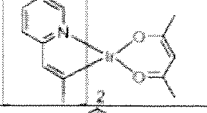
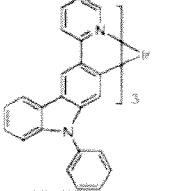
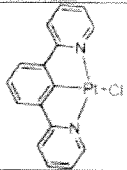
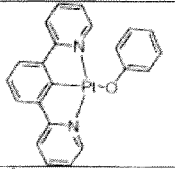
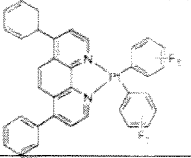
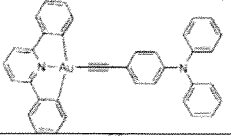
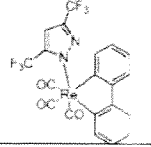
MATERIAL	EXAMPLES OF MATERIAL	PUBLICATIONS
Hole injection materials		
Phthalocyanine and porphyrin compounds		Appl. Phys. Lett. 69, 2160 (1996)
Starburst triarylaminines		J. Lumin. 72-74, 985 (1997)
CF _x Fluorohydrocarbon polymer	$\text{---}[\text{CH}_2\text{F}_y]_n\text{---}$	Appl. Phys. Lett. 78, 673 (2001)
Conducting polymers (e.g., PEDOT, PSS, polyaniline, polythiophene)		Synth. Met. 97, 171 (1997)
Arylamines complexed with metal oxides such as molybdenum and tungsten oxides		SID Symposium Digest, 37, 923 (2006)
Hole transporting materials		
Triarylaminines (e.g., TPD, α -NPD)		Appl. Phys. Lett. 51, 913 (1987)
		US5061569

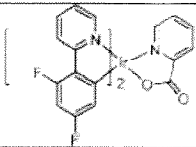
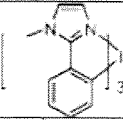
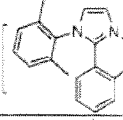
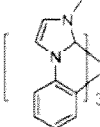
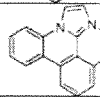
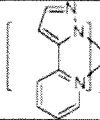
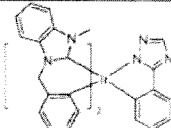
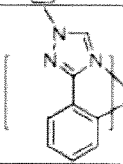
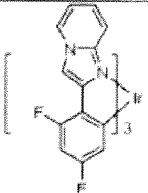
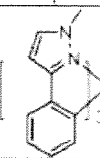
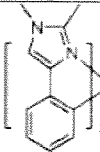
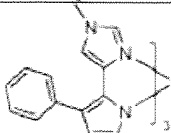
MATERIAL	EXAMPLES OF MATERIAL	PUBLICATIONS
		EP650955
		J. Mater. Chem. 3, 319 (1993)
		Appl. Phys. Lett. 90, 183503 (2007)
		Appl. Phys. Lett. 90, 183503 (2007)
Triarylamine on spirofluorene core		Synth. Met. 91, 209 (1997)
Arylamine carbazole compounds		Adv. Mater. 6, 677 (1994)
Indolocarbazoles		Synth. Met. 111, 421 (2000)
Isoindole compounds		Chem. Mater. 15, 3148 (2003)
Phosphorescent OLED host materials		
Red hosts		

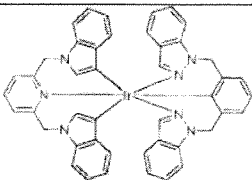
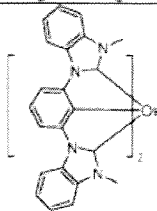
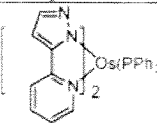
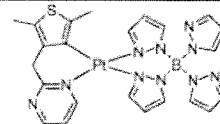
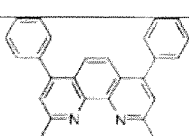
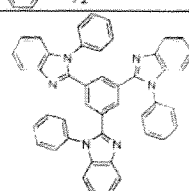
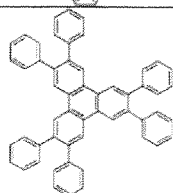
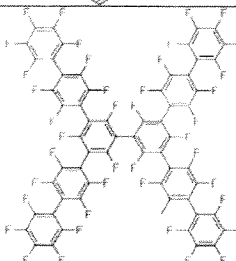
MATERIAL	EXAMPLES OF MATERIAL	PUBLICATIONS
Arylcarbazoles		Appl. Phys. Lett. 78, 1622 (2001)
Metal 8-hydroxyquinolates (e.g., Alq ₃ , BAlq)		Nature 395, 151 (1998)
		US20060202194
		WO2005014551
Metal phenoxybenzothiazole compounds		Appl. Phys. Lett. 90, 123509 (2007)
Conjugated oligomers and polymers (e.g., polyfluorene)		Org. Electron. 1, 15 (2000)
Green hosts		
Arylcarbazoles		Appl. Phys. Lett. 78, 1622 (2001)
		US2003175553
		WO2001039234
Aryltriphenylene compounds		US20060280965
		US20060280965
Polymers (e.g., PVK)		Appl. Phys. Lett. 77, 2280 (2000)
Spirofluorene compounds		WO2004093207
Metal phenoxybenzooxazole compounds		WO05089025
		WO06132173

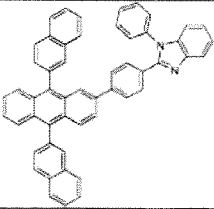
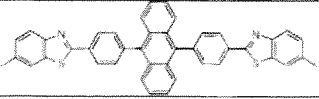
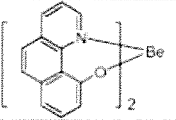
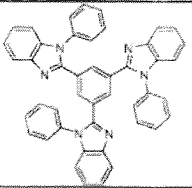
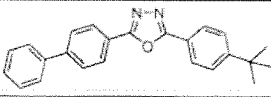
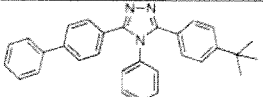
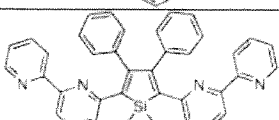
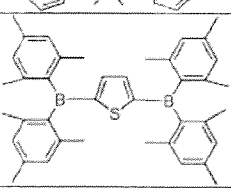
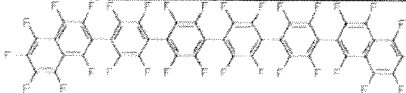
MATERIAL	EXAMPLES OF MATERIAL	PUBLICATIONS
		JP200511610
Spirofluorene-carbazole compounds		JP2007254297
		JP2007254297
Indolocabazoles		WO07063796
		WO07063754
5-member ring electron deficient heterocycles (e.g., triazole oxadiazole)		J. Appl. Phys. 90, 5048 (2001)
		WO04107822
Metal phenoxy pyridine compounds		WO05030900
Blue hosts		
Arylcarbazoles		Appl. Phys. Lett. 82, 2422 (2003)
		US20070190359
Dibenzothiophenecarbazole compounds		WO2006114966
Phosphorescent dopants		
Red dopants		
Heavy metal porphyrins (e.g., PtOEP)		Nature 395, 151 (1998)

MATERIAL	EXAMPLES OF MATERIAL	PUBLICATIONS
Iridium(III) organometallic complexes		Appl. Phys. Lett. 78, 1622 (2001)
		US06835469
		US20060202194
		US20060202194
		US07087321
		US07087321
		Adv. Mater. 19, 739 (2007)
		
Platinum(II) organometallic complexes		WO2003040257
Osmium(III) complexes		Chem. Mater. 17, 3532 (2005)
Ruthenium(II)		Adv. Mater. 17, 1059 (2005)
Green dopants		
Iridium(III) organometallic complexes		Inorg. Chem. 40, 1704
		US2002034656

MATERIAL	EXAMPLES OF MATERIAL	PUBLICATIONS
		US06687266
		Chem. Mater. 16, 2480 (2004)
		US2007190359
		US2006008670 JP2007123392
		Adv. Mater. 16, 2003 (2004)
		Agnew. Chem. Int. Ed. 2006, 45, 7800
Pt(II) organometallic complexes		Appl. Phys. Lett. 86, 153505 (2005)
		Appl. Phys. Lett. 86, 153505 (2005)
		Chem. Lett. 34, 592 (2005)
Gold Complexes		Chem. Commun. 2906 (2005)
Rhenium(III) complexes		Inorg. Chem. 42, 1248 (2003)
Blue dopants		

MATERIAL	EXAMPLES OF MATERIAL	PUBLICATIONS
Iridium(III) organometallic complexes		WO2002002714
		WO2006009024
		US2006251923
		WO2006056418, US2005260441
		US2007190359
		US2002134984
		Angew. Chem. Int. Ed. 47, 1 (2008)
		Chem. Mater. 18, 5119 (2006)
		Inorg. Chem. 46, 4308 (2007)
		WO05123873
		WO05123873
		WO07004380

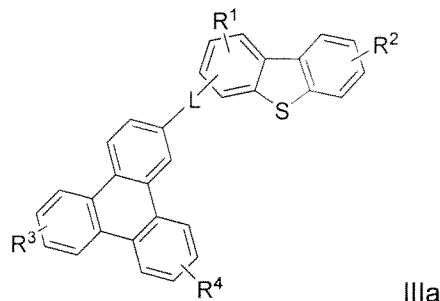
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		WO06082742
Osmium(II) complexes		US2005260449
		Organometallics 23, 3745 (2004)
Gold complexes		Appl. Phys. Lett. 74, 1361 (1999)
Platinum(II) complexes		WO06098120, WO06103874
Exciton/hole blocking layer materials		
Bathocuprine compounds (e.g., BCP, BPhen)		Appl. Phys. Lett. 75, 4 (1999)
		Appl. Phys. Lett. 79, 449 (2001)
Metal 8- hydroxyquinolates (e.g., BAlq)		Appl. Phys. Lett. 81, 162 162 (2002)
5-member ring electron deficient heterocycles such as triazole, oxadiazole, imidazole, benzoimidazole		Appl. Phys. Lett. 81, 162 162 (2002)
Triphenylene compounds		US20050025993
Flourinated aromatic compounds		Appl. Phys. Lett. 79, 156 (2001)

MATERIAL	EXAMPLES OF MATERIAL	PUBLICATIONS
Electron transporting materials		
Anthracene-benzoimidazole compounds		WO03060956
Anthracene-benzoimidazole compounds		Appl. Phys. Lett. 89, 063504 (2006)
Metal 8-hydroxybenzoquinolates (e.g., Alq ₃)		Appl. Phys. Lett. 51, 913 (1987)
Metal hydroxybenzoquinolates		Chem. Lett. 5, 905 (1993)
Bathocuprine compounds such as BCP, BPhen, etc		Appl. Phys. Lett. 1, 263503 (2007)
		Appl. Phys. Lett. 79, 449 (2001)
5-member ring electron deficient heterocycles (e.g., triazole, oxadiazole, imidazole, benzoimidazole)		Appl. Phys. Lett. 74, 865 (1999)
		Appl. Phys. Lett. 55, 1489 (1989)
		Jpn. J. Apply. Phys. 32, 1,917 (1993)
Silole compounds		Org. Electron. 4, 113 (2003)
Arylborane compounds		J. Am. Chem. Soc. 120, 9714 (1998)
Fluorinated aromatic compounds		J. Am. Chem. Soc. 122, 1832 (2000)

[0080] In embodiments, devices configured with the combination of materials disclosed herein may have a voltage below about 4.5 volts at 1,000 cd/m² and a luminance of at least 18,500 cd/m² at 40 mA/cm². Thus, in embodiments, there are provided organic light-emitting diode

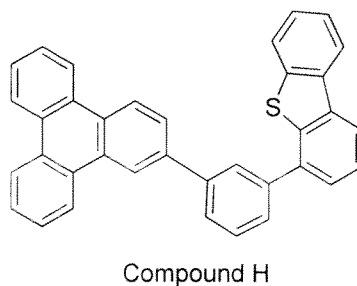
- (OLED) device comprising an emissive layer comprising a host material and a phosphorescent dopant, wherein the host material comprises a benzo-fused thiophene and the phosphorescent dopant comprises a heteroleptic transition metal complex having extended conjugation, and an electron transport layer disposed on the hole blocking layer, wherein the
- 5 OLED device has a luminous efficacy of at least about 40 lm/W and voltage below about 4.5 volts at 1,000 cd/m² (nits), and a luminance of at least 18,500 cd/m² at 40 mA/cm².

[0081] In some such embodiments, the benzo-fused thiophene comprises a compound of Formula IIIa:



- 10 wherein each R¹ and R² are independently selected from the group consisting of alkyl, alkoxy, amino, alkenyl, alkynyl, arylalkyl, aryl, aralkyl, heteroaryl, and hydrogen; L is bond or an optionally substituted phenyl group; and R³ and R⁴ are independently selected from the group

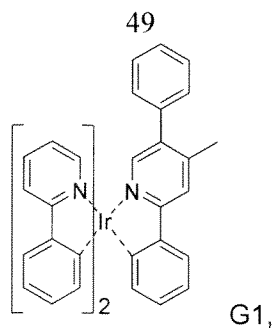
consisting of hydrogen and  such as, for example, Compound H below:



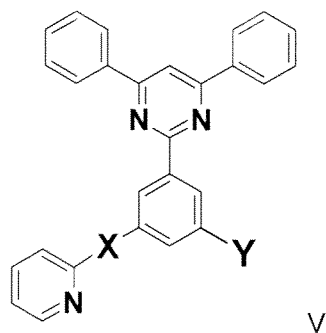
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[0082] In some such embodiments, the heteroleptic transition metal complex is a compound of Formula L₂MX, LL'MX, LL'L'M, or LMXX', wherein L, L', L'', X, and X' are inequivalent, bidentate ligands and M is a transition metal that forms octahedral complexes, wherein L, L', and L'' are monoanionic inequivalent bidentate ligands coordinated to M through an sp²

20 hybridized carbon and a heteroatom such as, for example, Compound G1 below:

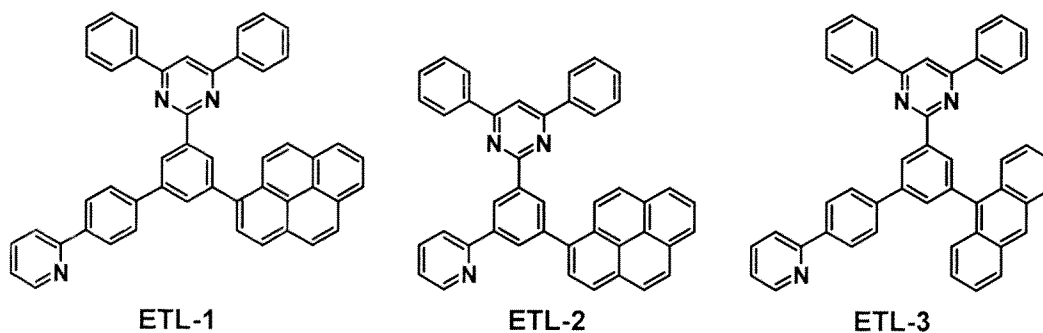


and the electron transport layer comprises a compound of Formula V:



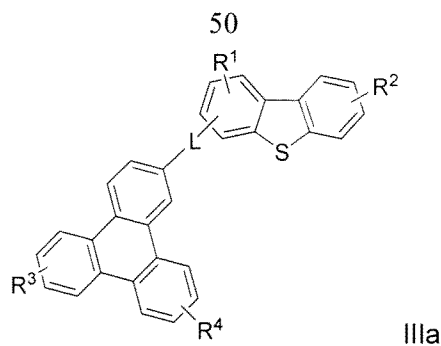
where X represents a single chemical bond or phenylene group, and Y represents anthracenyl group or pyrenyl group.

[0083] Exemplary compounds of structure V include structures ETL-1, ETL-2, and ETL-3 below:



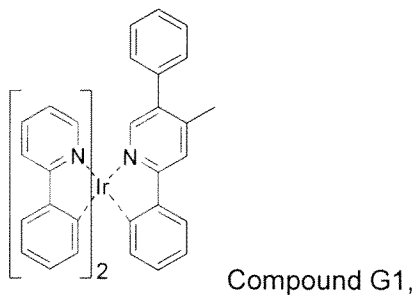
[0084] In embodiments, such devices may also exhibit a time for luminance to decrease to 97% of its initial level of about 50 hours at 10,000 cd/m².

[0085] In embodiments, there are provided organic light-emitting diode (OLED) devices comprising an emissive layer comprising a host material and a phosphorescent dopant, wherein the host material comprises a benzo-fused thiophene compound of Formula H-IIIa:

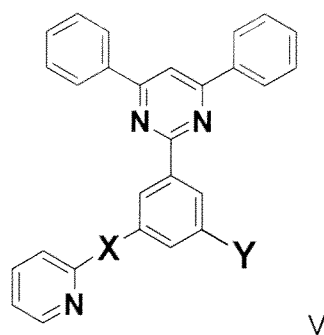


wherein each R^1 and R^2 are independently selected from the group consisting of alkyl, alkoxy, amino, alkenyl, alkynyl, arylalkyl, aryl, aralkyl, heteroaryl, and hydrogen; L is bond or an optionally substituted phenyl group; and R^3 and R^4 are independently selected from the group

- 5 consisting of hydrogen and , and the phosphorescent dopant comprises Compound G1:



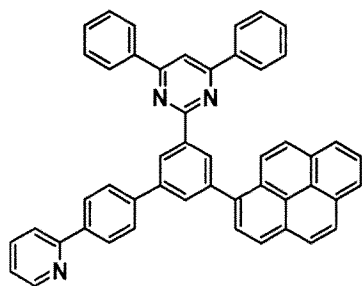
- 10 ; and an electron transport layer disposed over the emissive layer, wherein the electron transport layer comprises a compound of Formula V:



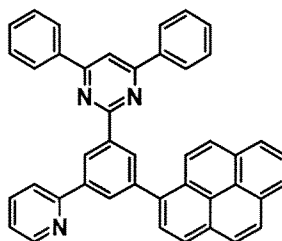
where X represents a single chemical bond or phenylene group, and Y represents anthracenyl group or pyrenyl group.

- 15 [0086] Exemplary compounds of structure V include structures ETL-1, ETL-2, and ETL-3 below:

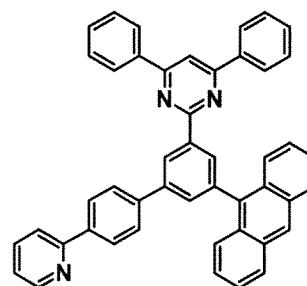
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ETL-1



ETL-2



ETL-3

[0087] In embodiments, such devices may further comprise a hole blocking layer between the emissive layer and the electron transport layer, the hole blocking layer comprising a hole blocking material that may be the same or different from the host material in the emissive layer. In embodiments, the hole blocking material may be a benzo fused thiophene compound. In embodiments, the hole blocking material may be the same benzo fused thiophene compound as the host material in the emissive layer.

EXAMPLES

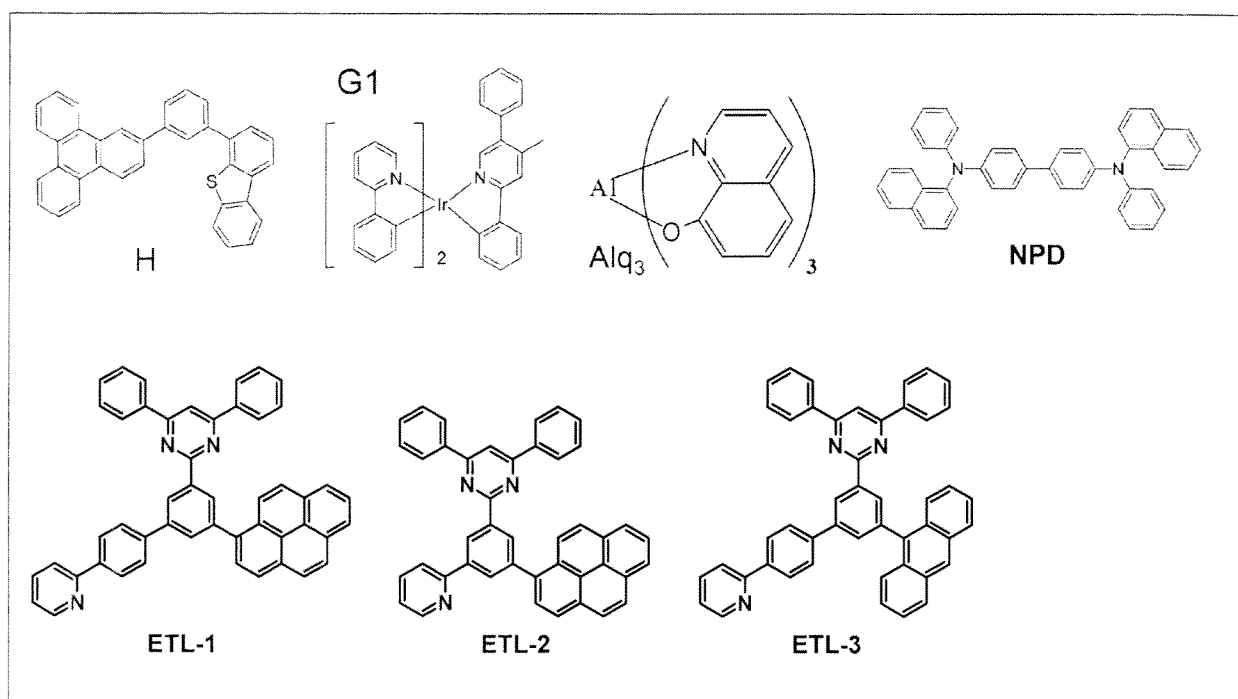
EXAMPLE 1

[0088] This Example shows the preparation and performance of devices prepared from the synergistic combination of materials disclosed herein.

DEVICE FABRICATION AND MEASUREMENT

[0089] Experimental Devices #1, #2 and #3 all bearing the structure shown in FIG. 3 were fabricated according to the present disclosure as follows: LG101 (LGChem, Seoul, South Korean) was used in all devices to form a 10 nm thick hole injection layer. NPD was used in all devices to form a 30 nm thick hole transport layer. In all devices, phosphorescent emitter compound **G1** (previously disclosed as Compound 12 in WO2010/028151 including synthesis) was doped at 12 % doping level into Compound **H** as a host material (previously disclosed as Compound 2' in WO 2009/021126 including synthesis) to form a 30 nm thick emissive layer layer. An undoped layer of compound **H** was used in all devices to form a 5 nm thick hole blocking layer. A 40 nm thick electron transport layer was deposited over the hole blocking layer using one of ETL-1, ETL-2 and ETL-3 respectively in Devices #1, #2, #3. LiF was used in all devices to form 1 nm thick electron injection layer. A 100 nm thick layer of Aluminum formed the cathode in all devices and an 80 nm thick layer of ITO formed the anode in all devices. The chemical structures of experimental electron transport compounds ETL-1, ETL-2 and ETL-3, comparative electron transport compound Alq3, hole blocking/host compound **H**, dopant compound **G1** and hole transport compound NPD are shown in Table 2 below. Hole injection material LG101 was obtained from LG Chem, Seoul, South Korea.

Table 2



[0090] All organic layers were deposited under high-vacuum conditions (1×10^{-7} Torr).

The device was transferred directly from vacuum into an inert environment glove-box, where it was encapsulated using a UV-curable epoxy, and a glass lid with a moisture getter. The emission profiles were assumed to be Lambertian, so EQE was calculated from measurements, made with a SpectraScan PR705, of the emission intensity normal to the substrate. The current and voltage measurements were obtained using a Keithley 236 source measure unit.

[0091] For performance comparison, Comparative Example Device CE, also bearing the structure shown in FIG. 3, was also constructed. Comparative Example Device CE was fabricated in the same manner as Experimental devices #1, #2 and #3 except that Alq₃ was used to form the electron transport layer rather than ETL-1, ETL-2 or ETL-3.

[0092] Table 2 shows a summary of the four devices' construction in terms of the materials used for the electron transporting layer and the emitter layer. Table 3 shows the performance comparison of Experimental Devices #1, #2 and #3 and Comparative Example device CE.

TABLE 2

Device #	Electron Transport Material	Emitter Dopant	Emitter Host
1	ETL 1	heteroleptic organometallic compound G1	triphenylene containing benzo-fused thiophene compound H
2	ETL 2	heteroleptic organometallic compound G1	triphenylene containing benzo-fused thiophene compound H

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3	ETL 3	heteroleptic organometallic compound G1	triphenylene containing benzo-fused thiophene compound H
CE	Alq ₃	heteroleptic organometallic compound G1	triphenylene containing benzo-fused thiophene compound H

Table 3

ETL	1931 CIE		At 1000 nits					At 10,000 nits		At 40mA/cm ²	
	x	y	λ max [nm]	FWHM [nm]	Voltage [V]	LE [cd/A]	EQE [%]	PE [lm/W]	LT97% [h]	Lo [nits]	LT _{97%} [h]
1	0.324	0.625	522	66	4.3	66	18	49	37	18,600	12
2	0.322	0.629	524	64	4.3	76	21	55	51	22,023	12
3	0.321	0.630	524	64	3.9	76	21	61	38	21,600	9
Comparative Example Alq ₃	0.317	0.629	522	64	4.9	58	16	37	38	17,647	14

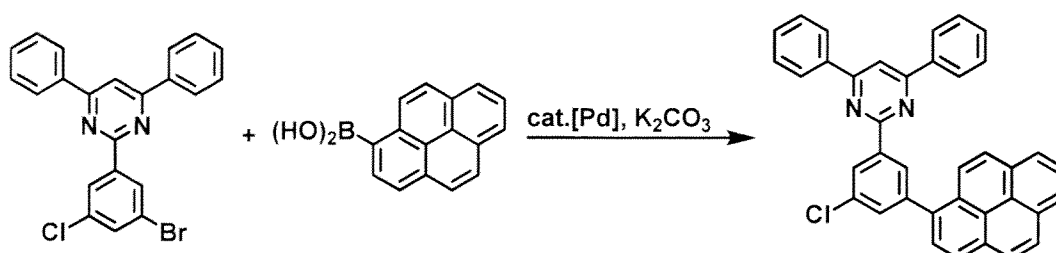
- 5 [0093] As seen in Table 3, the power efficacies of devices in accordance with embodiments disclosed herein using ETL-1, ETL-2 or ETL-3 as electron transport material in combination with H:G1(12%) were 49, 55, and 61 lm/W at 1,000 nits respectively compared to 37 lm/W for comparative device using previously known Alq₃ as ETL material. Devices #1 and #3 achieved the higher efficiency while maintaining comparable operational lifetime.
- 10 Device #2 demonstrated improved operational lifetime in addition to higher efficiency. The LT97 (time for luminance to decrease to 97% of its initial level) at 10,000 nits was estimated to be 51 hrs for Device #2 compared to 38 hours for Device CE using known ETL material Alq.

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EXAMPLE 2

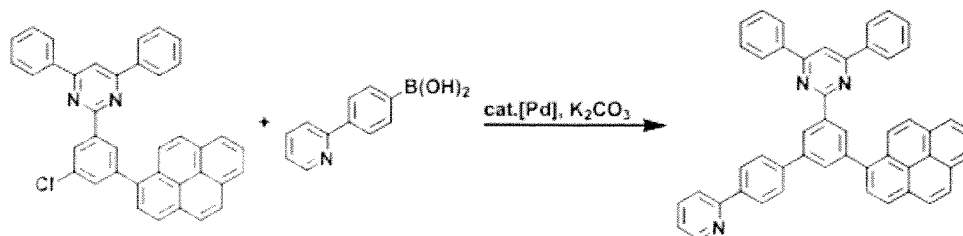
[0094] This example shows the preparation of exemplary electron transport materials.

[0095] Synthesis of ETL-1



[0096] In a stream of argon, 7.0 g of 2-(3-bromo-5-chlorophenyl)-4,6-diphenylpyrimidine, 4.5 g of 1-pyreneboronic acid, 117 mg of bis(triphenylphosphine)palladium dichloride, and 17 mL of aqueous 4N-NaOH solution were suspended in 75 mL of THF, and the resultant suspension was heated under reflux for one hour. Then, the suspension was cooled to room temperature, and water and methanol were added to the suspension. The deposited solid was collected by filtration and rinsed with water and with methanol to give 1.24 g of 4,6-diphenyl -2-[3-chloro-5-(1-pyrenyl)phenyl]pyrimidine as a pale yellow powder (yield:99%).

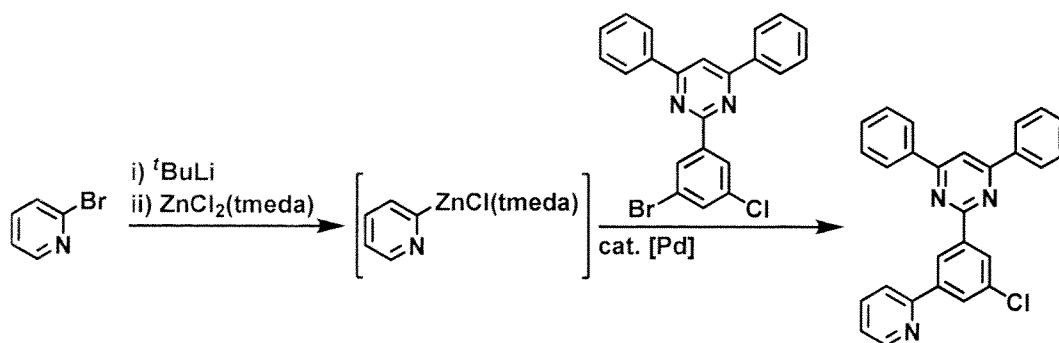
[0097] $^1\text{H-NMR}$ (400 MHz, CDCl_3) δ (ppm): 7.54-7.58 (m, 6H), 7.79 (s, 1H), 8.07 (t, $J = 7.6$ Hz, 1H), 8.09-8.12 (m, 3H), 8.17 (s, 2H), 8.22-8.32 (m, 8H), 8.86 (s, 1H), 8.89(s, 1H).



[0098] In a stream of argon, 6.5 g of 4,6-diphenyl -2-[3-chloro-5-(1-pyrenyl)phenyl]pyrimidine, 2.9 g of 4-(2-pyridyl)phenylboronic acid, 26.9 mg of palladium(II) acetate, 171 mg of 2-dicyclohexylphosphino-2',4',6'-triisopropylbiphenyl, and 9.6 mL aqueous 3M- K_2CO_3 solution were suspended in a mixed solvent composed of 54 mL of toluene and 6.0 mL of 1-butanol, and the resultant suspension was heated to 100 degree Celsius and maintained at that temperature for 3 hours while being stirred. Then, the suspension was cooled to room temperature, and water and methanol were added to the suspension. The deposited solid was collected by filtration and rinsed with water and with methanol to give 7.53 g of 4,6-diphenyl -2-[5-(1-pyrenyl)-4'-(2-pyridyl)biphenyl-3-yl]pyrimidine (ETL-1) as a yellow powder (yield:98%).

[0099] $^1\text{H-NMR}$ (400 MHz, CDCl_3) δ (ppm): 7.26-7.30 (m, 1H), 7.55-7.60 (m, 6H), 7.80 (t, $J = 7.6$ Hz, 1H), 7.85 (d, $J = 7.0$ Hz, 1H), 8.01 (d, $J = 8.5$ Hz, 2H), 8.06 (t, $J = 7.6$ Hz, 1H), 8.09-8.11 (m, 3H), 8.17-8.23 (m, 6H), 8.25 (d, $J = 7.6$ Hz, 1H), 8.31-8.38 (m, 6H), 8.76 (d, $J = 4.8$ Hz, 1H), 9.02 (s, 1H), 9.19 (s, 1H).

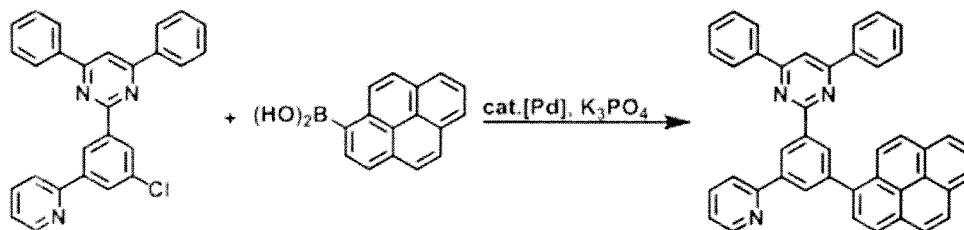
[00100] Synthesis of ETL-2



[00101] In a stream of argon, a solution of 2.84 g of 2-bromopyridine and 75 mL of THF was cooled to -78 degree Celsius. 23.3 mL of 1.61M tert-butyl lithium in pentane was added dropwise into the solution. The resultant mixture was being stirred for 30 minutes at -78 degree Celsius, and then 6.8 g of $\text{ZnCl}_2\text{-N,N,N',N'}$ -tetramethylethylenediamine complex was added to the cooled mixture. The resultant mixture was warmed to room temperature while being stirred. Then 6.3 g of 2-(3-bromo-5-chlorophenyl)-4,6-diphenylpyrimidine and 347 mg of tetrakis(triphenylphosphine)palladium was added into the warmed mixture. The resultant mixture was distilled under the reduce pressure to remove pentane, and then was heated under reflux for 3 hours while being stirred, and then was cooled to room temperature.

10 Saturated aqueous NH_4Cl solution was added to the mixture, and the resultant mixture was extracted with chloroform. The obtained crude product was purified by silica gel chromatography to give 5.5 g of 4,6-diphenyl-2-[3-chloro-5-(2-pyridyl)phenyl]pyrimidine as a pale yellow powder (yield:87%).

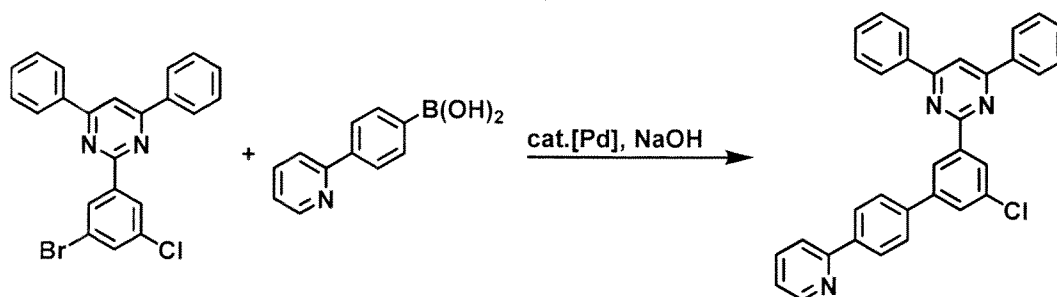
[00102] $^1\text{H-NMR}$ (400 MHz, CDCl_3) δ (ppm): 7.34 (dd, $J = 7.4, 4.8$ Hz, 1H), 7.57-7.64 (m, 6H), 7.87 (t, $J = 7.7$ Hz, 1H), 7.94 (d, $J = 8.0$ Hz, 1H), 8.10 (s, 1H), 8.25 (s, 1H), 8.31-8.35 (m, 4H), 8.78-8.80 (m, 2H), 9.18 (s, 1H).



[00103] In a stream of argon, 1.0 g of 4,6-diphenyl-2-[3-chloro-5-(2-pyridyl)phenyl]pyrimidine, 645 mg of 1-pyreneboronic acid, 10.7 mg of palladium(II) acetate, 20 68 mg of 2-dicyclohexylphosphino-2',4',6'-triisopropylbiphenyl, and 1.6 mL of aqueous 3M-potassium phosphate solution were suspended in a mixed solvent composed of 9.5 mL of toluene and 2.4 mL of 1-butanol, and the resultant suspension was heated to 100 degree Celsius and maintained at that temperature for 19 hours. Then, the suspension was cooled to room temperature, and water and methanol was added to the suspension. The deposited solid 25 was collected by filtration and rinsed with water and with methanol to give 1.35 g of 4,6-diphenyl -2-[5-(1-pyrenyl)-3-(2-pyridyl)phenyl]pyrimidine (ETL-2) as a yellow powder (yield:97%).

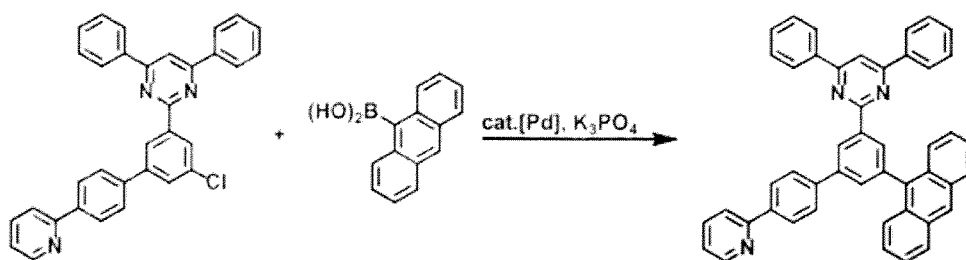
[00104] $^1\text{H-NMR}$ (400 MHz, CDCl_3) δ (ppm): 7.34 (dd, $J = 7.6, 4.8$ Hz, 1H), 7.54-7.60 (m, 6H), 7.88 (t, $J = 7.6$ Hz, 1H), 8.03-8.11 (m, 4H), 8.15-8.23 (m, 4H), 8.25 (d, $J = 7.6$ Hz, 1H), 8.32-8.35 (m, 6H), 8.49 (s, 1H), 8.81 (d, $J = 4.8$ Hz, 1H), 9.07 (s, 1H), 9.44 (s, 1H).

[00105] Synthesis of ETL-3



[00106] In a stream of argon, 8.4 g of 2-(3-bromo-5-chlorophenyl)-4,6-diphenylpyrimidine, 4.4 g of 4-(2-pyridyl)phenylboronic acid, 328 mg of tetrakis(triphenylphosphin)palladium, and 7.5 mL of aqueous 4N-NaOH solution were suspended in 100 mL of THF, and the resultant suspension was heated under reflux for 24 hours. Then, the suspension was cooled to room temperature. Water was added to the suspension, and the resultant suspension was extracted with chloroform. The obtained crude product was purified by silica gel chromatography by using a chloroform as an eluent to give 8.3 g of 4,6-diphenyl-2-[5-chloro-4'-(2-pyridyl)biphenyl-3-yl]pyrimidine as a white powder (yield:83%).

[00107] $^1\text{H-NMR}$ (400 MHz, CDCl_3) δ (ppm): 7.28-7.32 (m, 1H), 7.59-7.64 (m, 6H), 7.80-7.85 (m, 3H), 7.87 (d, $J = 8.5$ Hz, 2H), 8.11 (s, 1H), 8.18 (d, $J = 8.5$ Hz, 2H), 8.32-8.35 (m, 4H), 8.74 (s, 1H), 8.77 (d, $J = 4.8$ Hz, 1H), 8.93 (s, 1H).



[00108] In a stream of argon, 600 mg of 4,6-diphenyl-2-[5-chloro-4'-(2-pyridyl)biphenyl-3-yl]pyrimidine, 403 mg of 9-anthraceneboronic acid, 5.4 mg of palladium(II) acetate, 34.2 mg of 2-dicyclohexylphosphino-2',4',6'-triisopropylbiphenyl, and 1.2 mL of aqueous 3M-potassium phosphate solution were suspended in a mixed solvent composed of 4.8 mL of toluene and 1.2 mL of 1-butanol, and the resultant suspension was heated to 100 degree Celsius and maintained at that temperature for 2 hours. Then, the suspension was cooled to room temperature, and water was added to the suspension. The resultant suspension was extracted with chloroform. The obtained organic layer was distilled under reduce pressure to remove volatile materials to give 584 mg of 4,6-diphenyl-2-[5-(9-anthracenyl)-4'-(2-pyridyl)biphenyl-3-yl]pyrimidine (ETL-3) as a yellow powder (yield:76%).

[00109] $^1\text{H-NMR}$ (400 MHz, CDCl_3) δ (ppm): 7.27 (t, $J = 6.2$ Hz, 1H), 7.41 (d, $J = 6.5$ Hz, 1H), 7.44 (d, $J = 6.6$ Hz, 1H), 7.51-7.60 (m, 8H), 7.80 (t, $J = 7.5$ Hz, 1H), 7.83 (d, $J = 7.7$ Hz, 1H), 7.90 (d, $J = 8.8$ Hz, 2H), 7.94 (s, 1H), 7.99 (d, $J = 8.5$ Hz, 2H), 8.11 (s, 1H), 8.14 (d, $J =$

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8.5 Hz, 2H), 8.18 (d, J = 8.5 Hz, 2H), 8.29-8.32 (m, 4H), 8.62 (s, 1H), 8.76 (d, J = 4.8 Hz, 1H), 8.85 (s, 1H), 9.28 (s, 1H)..

[00110] Any of ETL-1, ETL-2 or ETL-3 synthesized above may be further refined by sublimation under vacuum before its use for the provision of the layered structure, in

5 accordance with embodiments disclosed herein.

CONCLUSIONS

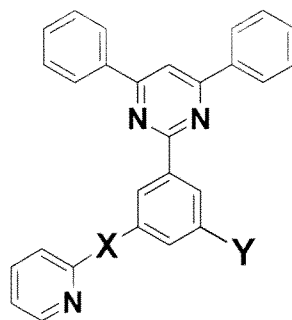
[00111] OLEDs incorporating the teachings of the present disclosure exhibit unexpected and substantial improved working lifetime characteristics and improved luminous efficiency

[00112] . Disclosed is an organic light emitting device comprising an anode, a cathode and a plurality of organic layers sandwiched between them, the plurality of organic layers comprising:

10 an emitter layer comprising a host material and a phosphorescent emitter material wherein the host material comprises a triphenylene containing benzo-fused thiophene or benzo-fused furan and wherein the phosphorescent emitter material comprises a phosphorescent organometallic compound that emits phosphorescent radiation from a triplet molecular excited state when a

15 voltage is applied across the device;

an electron transport layer disposed between the emitter layer and the cathode, the electron transport layer comprising an electron transport material represented by the following general formula V:



20 where X represents a single chemical bond or phenylene group, and Y represents anthracenyl group or pyrenyl group

[00113] According to the disclosed is an organic light emitting device, the phosphorescent organometallic compound is selected from the group consisting of phosphorescent organometallic platinum compounds, organometallic iridium compounds and

25 organometallic osmium compounds

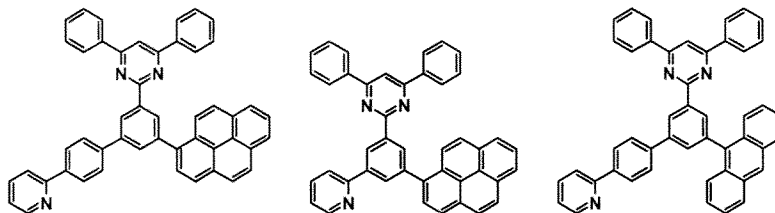
[00114] According to an embodiment of the disclosed organic light emitting device, the phenylene group may be selected from 1,2-phenylene, 1,3-phenylene and 1,4-phenylene.

[00115] According to the disclosed is an organic light emitting device, the phosphorescent organometallic compound may comprise an aromatic ligand.

30 [00116] According to an embodiment of the disclosed organic light emitting device, the anthracenyl group is selected from anthracen-9-yl, anthracen-1-yl and anthracen-2-yl.

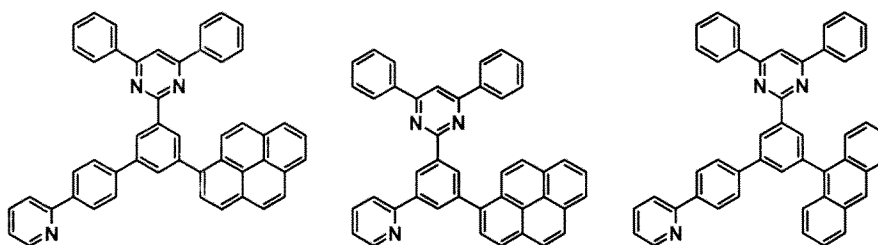
[00117] According to an embodiment of the disclosed organic light emitting device, the pyrenyl group is selected from pyren-1-yl, pyren-2-yl and pyren-4-yl.

[00118] According to an embodiment of the disclosed organic light emitting device, the electron transport material is selected from the group consisting of:

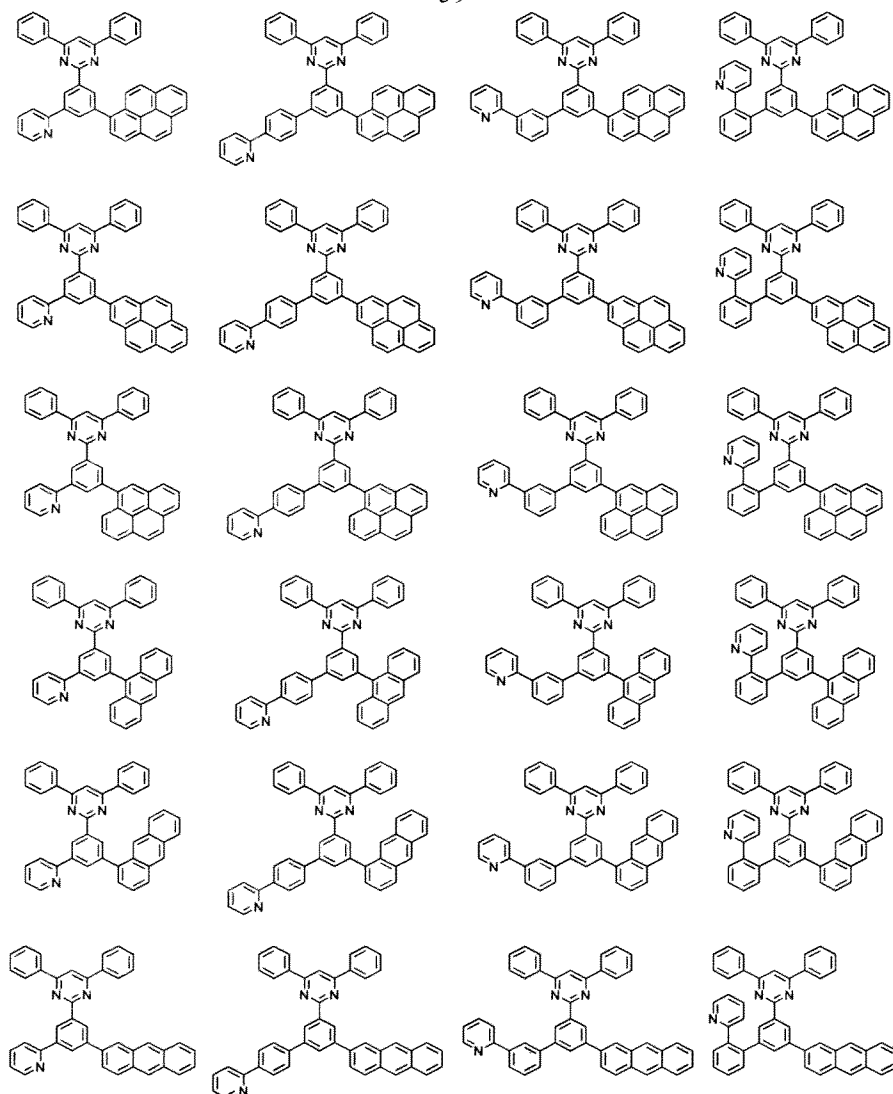


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[00119] According to an embodiment of the disclosed organic light emitting device, the electron transport material is selected from the group consisting of:

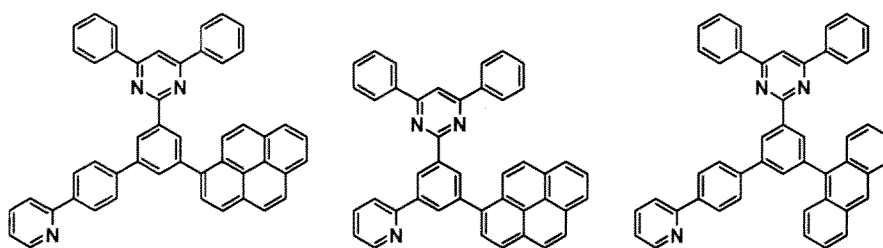


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[00120] According to another embodiment of the disclosed organic light emitting device, the electron transport material is selected from the group consisting of

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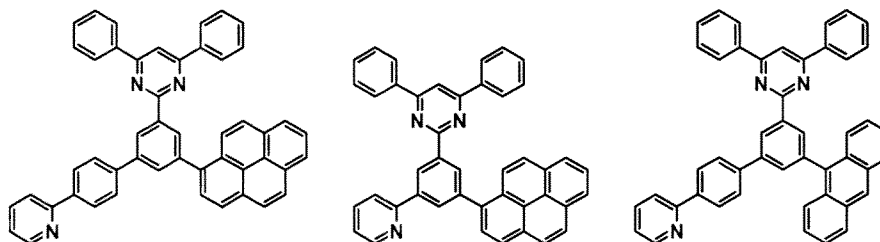
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and the host material is a compound comprising a triphenylene containing benzo-fused thiophene or benzo-fused furan, wherein any substituent in the compound is an unfused substituent independently selected from the group consisting of C_nH_{2n+1} , OC_nH_{2n+1} , OAr_1 , $N(C_nH_{2n+1})_2$, $N(Ar_1)(Ar_2)$, $CH=CH-C_nH_{2n+1}$, $C=CHC_nH_{2n+1}$, Ar_1 , Ar_1-Ar_2 , $C_nH_{2n}-Ar_1$, or no substitution, wherein n is 1, 2, 3, 4, 5, 6, 7, 8, 9, or 10, and wherein Ar_1 and Ar_2 are

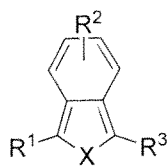
independently selected from the group consisting of benzene, biphenyl, naphthalene, triphenylene, carbazole, and heteroaromatic analogs thereof 000000000000

[00121] According to another embodiment of the disclosed organic light emitting device, the electron transport material is selected from the group consisting of:

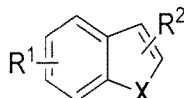
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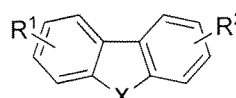
And the host material is represented by the structure of formula (H-IV), (H-V) or (H-VI):



(H-IV)



(H-V)



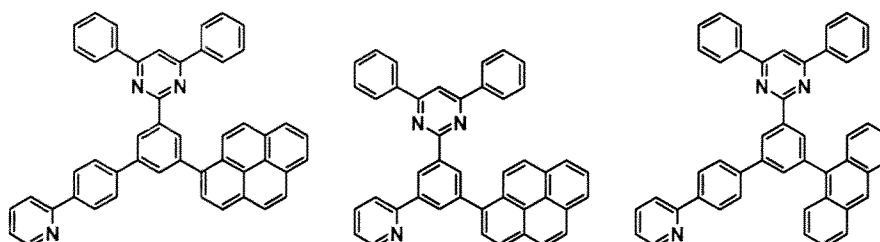
(H-VI)

where X is S or O and wherein R^1 , R^2 and R^3 are unfused substituents that are independently selected from C_nH_{2n+1} , OC_nH_{2n+1} , OAr_1 , $N(C_nH_{2n+1})_2$, $N(Ar_1)(Ar_2)$, $CH=CH-C_nH_{2n+1}$,

10 $C=CHC_nH_{2n+1}$, Ar_1 , Ar_1-Ar_2 , $C_nH_{2n}-Ar_1$, or no substitution. Each of R^1 , R^2 and R^3 may represent mono, di, tri, or tetra substitutions, n is 1, 2, 3, 4, 5, 6, 7, 8, 9, or 10. Ar_1 and Ar_2 are independently selected from the group consisting of benzene, biphenyl, naphthalene, triphenylene, carbazole, and heteroaromatic analogs thereof. At least one of R^1 , R^2 and R^3 in Formula (H-IV) and at least one of R^1 and R^2 in Formulas (H-V) and (H-VI) includes a

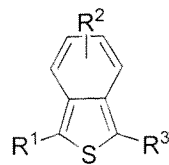
15 triphenylene group.

[00122] According to another embodiment of the disclosed organic light emitting device, the electron transport material is selected from the group consisting of:

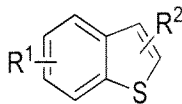


And the host material is represented by the structure of formula (H-I) (H-II) (H-III):

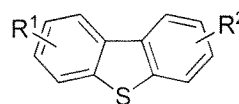
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(H-I)



(H-II)



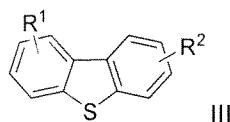
(H-III)

- Where R^1 , R^2 and R^3 are independently selected from alkyl, alkoxy, amino, alkenyl, alkynyl, arylkyl, aryl, heteroaryl and hydrogen. Each of R^1 , R^2 and R^3 may represent multiple substituents. At least one of R^1 , R^2 and R^3 in Formula (H-I) and at least one of R^1 and R^2 in Formulas (H-II) and (H-III) includes a triphenylene group.

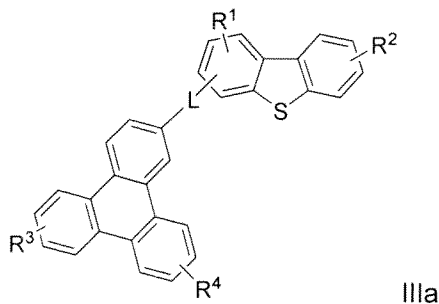
- [00123]** According to another embodiment of the disclosed organic light emitting device, the device further comprise a hole blocking layer disposed between the emissive layer and the electron transport layer, the hole blocking layer comprising a hole blocking material that may be the same or different from the host material in the emissive layer.
- 10 **[00124]** According to another embodiment of the disclosed organic light emitting device, the device further comprise a hole blocking layer disposed between the emissive layer and the electron transport layer, the hole blocking layer comprising a hole blocking material that is the same as the host material in the emissive layer.

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CLAIMS

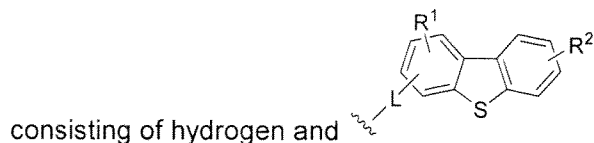
1. An organic light-emitting diode (OLED) device comprising:
an emissive layer comprising a host material and a phosphorescent dopant;
5 wherein the host material comprises a benzo-fused thiophene and the phosphorescent dopant comprises a heteroleptic transition metal complex having extended conjugation;
a hole blocking layer disposed on the emissive layer, the hole blocking layer comprising a hole blocking material;
an electron transport layer disposed on the hole blocking layer
10 wherein the OLED device has a luminous efficacy of at least about 40 lm/W at 1,000 cd/m² (nits).
2. The device of claim 1, wherein the benzo-fused thiophene comprises a compound of Formula III:



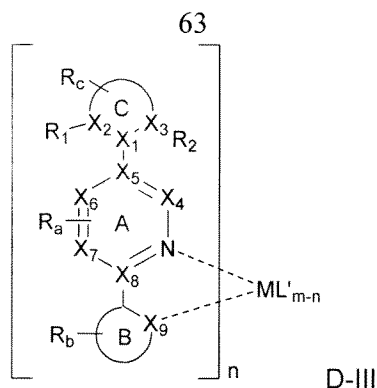
- 15 wherein R¹ and R² are independently selected from the group consisting of alkyl, alkoxy, amino, alkenyl, alkynyl, arylalkyl, aryl, aralkyl, heteroaryl, and hydrogen.
3. The device of claim 2, wherein the benzo-fused thiophene comprises a compound of Formula IIIa:



- 20 wherein each R¹ and R² are independently selected from the group consisting of alkyl, alkoxy, amino, alkenyl, alkynyl, arylalkyl, aryl, aralkyl, heteroaryl, and hydrogen; L is bond or an optionally substituted phenyl group; and R³ and R⁴ are independently selected from the group

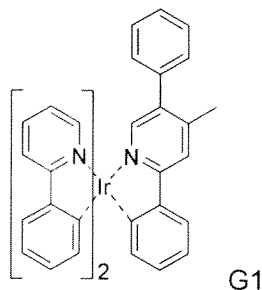


4. The device of claim 1, wherein the heteroleptic transition metal complex comprises a
25 compound of Formula D-III:



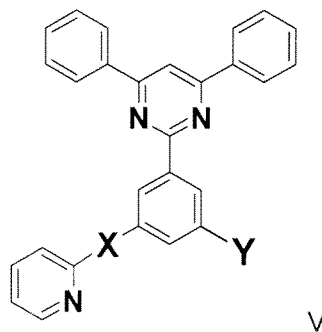
wherein B and C are each independently a 5 or 6-membered carbocyclic or heterocyclic rings; wherein A-B is a bonded pair of carbocyclic or heterocyclic rings coordinated to a metal M via a nitrogen atom in ring A and an sp^2 hybridized atom in ring B; wherein A-C is a bonded pair of carbocyclic or heterocyclic rings; wherein each R_a , R_b , and R_c are independently mono, di, tri, or tetra substitutions and each R_a , R_b , and R_c are independently selected from the group consisting of hydrogen, alkyl, alkoxy, amino, alkenyl, alkynyl, arylkyl, aryl, and heteroaryl, any of which may be optionally substituted; wherein X_1 , X_2 , X_3 , X_4 , X_5 , X_6 , X_7 , X_8 , and X_9 are independently selected from carbon and nitrogen; wherein R_1 and R_2 are independently selected from the group consisting of hydrogen, alkyl, alkoxy, amino, alkenyl, alkynyl, arylkyl, aryl, and heteroaryl, any of which may be optionally substituted; and wherein at least one of R_1 , R_2 , and the R_a substituents adjacent to C is not hydrogen; wherein M is a coordinated metal having an atomic number greater than 40, m is the oxidation state of the metal, and n is an integer of at least 1.

5. The device of claim 4, wherein the heteroleptic transition metal complex is Compound G1 :

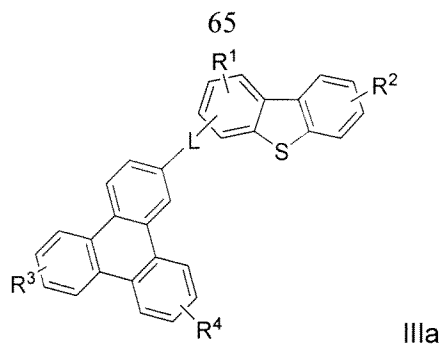


6. The device of claim 1, wherein the host material and hole blocking material are the same.

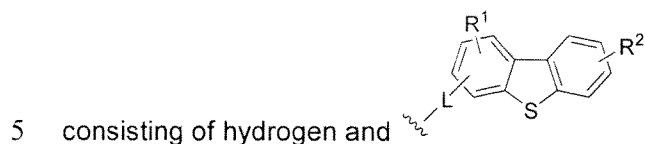
7. The device of claim 1, wherein the electron transport layer comprises a compound of Formula V:



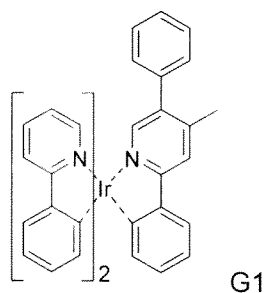
- 5 wherein X represents a single chemical bond or phenylene group, and Y represents an anthracenyl group or pyrenyl group
8. The device of claim 1, wherein phosphorescent dopant is present in a range from about 5 percent to about 15 percent by weight of the layer.
9. The device of claim 1, wherein the emissive layer has a thickness from about 200
- 10 angstroms to about 400 angstroms.
10. The device of claim 1, wherein the hole blocking layer has a thickness from about 25 to about 75 angstroms.
11. The device of claim 1, wherein the electron transport layer has a thickness from about 350 angstroms to about 550 angstroms.
- 15 12. The device of claim 1, having a voltage below about 4.5 volts at 1,000 cd/m².
13. The device of claim 1, having a luminance of at least 18,500 cd/m² at 40 mA/cm².
14. An organic light-emitting diode (OLED) device comprising:
 an emissive layer comprising a host material and a phosphorescent dopant;
 wherein the host material comprises a benzo-fused thiophene and the phosphorescent
 20 dopant comprises a heteroleptic transition metal complex having extended conjugation;
 a hole blocking layer disposed on the emissive layer, the hole blocking layer comprising a hole blocking material; and
 an electron transport layer disposed on the hole blocking layer;
 wherein the OLED device has a luminous efficacy of at least about 40 lm/W and voltage
 25 below about 4.5 volts at 1,000 cd/m² (nits), and a luminance of at least 18,500 cd/m² at 40 mA/cm².
15. The device of claim 14, wherein the benzo-fused thiophene comprises a compound of Formula IIIa:



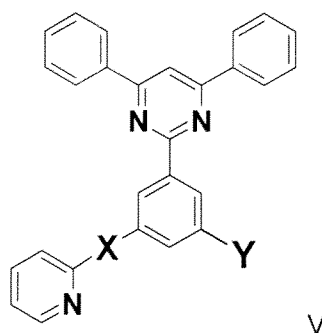
wherein each R^1 and R^2 are independently selected from the group consisting of alkyl, alkoxy, amino, alkenyl, alkynyl, arylalkyl, aryl, aralkyl, heteroaryl, and hydrogen; L is bond or an optionally substituted phenyl group; and R^3 and R^4 are independently selected from the group



16. The device of claim 14, wherein the heteroleptic transition metal complex is Compound G1:



17. The device of claim 14, wherein the electron transport layer comprises a compound of
10 Formula V:



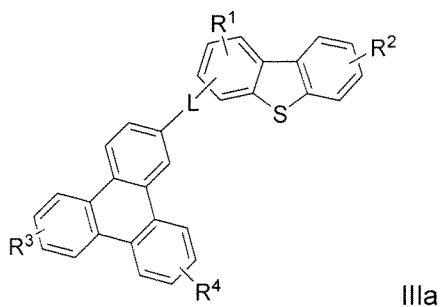
wherein X represents a single chemical bond or phenylene group, and Y represents anthracenyl group or pyrenyl group

18. The device of claim 14, wherein the device has a time for luminance to decrease to 97%
15 of its initial level of about 50 hours at 10,000 cd/m².

19. An organic light-emitting diode (OLED) device comprising:
an emissive layer comprising a host material and a phosphorescent dopant;

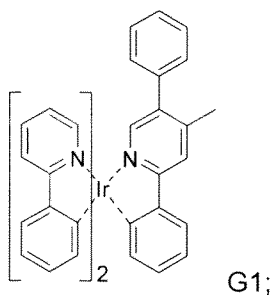
66

wherein the host material comprises benzo-fused thiophene comprises a compound of Formula IIIa:

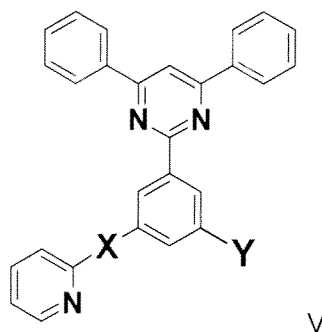


- wherein each R^1 and R^2 are independently selected from the group consisting of alkyl, alkoxy, amino, alkenyl, alkynyl, arylalkyl, aryl, aralkyl, heteroaryl, and hydrogen; L is bond or an optionally substituted phenyl group; and R^3 and R^4 are independently selected from the group

consisting of hydrogen and ; and the phosphorescent dopant comprises Compound G1:



- a hole blocking layer disposed on the emissive layer, the hole blocking layer comprising a hole blocking material; and an electron transport layer disposed on the hole blocking layer; wherein the electron transport layer comprises a compound of Formula V:



- wherein X represents a single chemical bond or phenylene group, and Y represents anthracenyl group or pyrenyl group
20. The device of claim 19, wherein the host material and hole blocking material are the same.

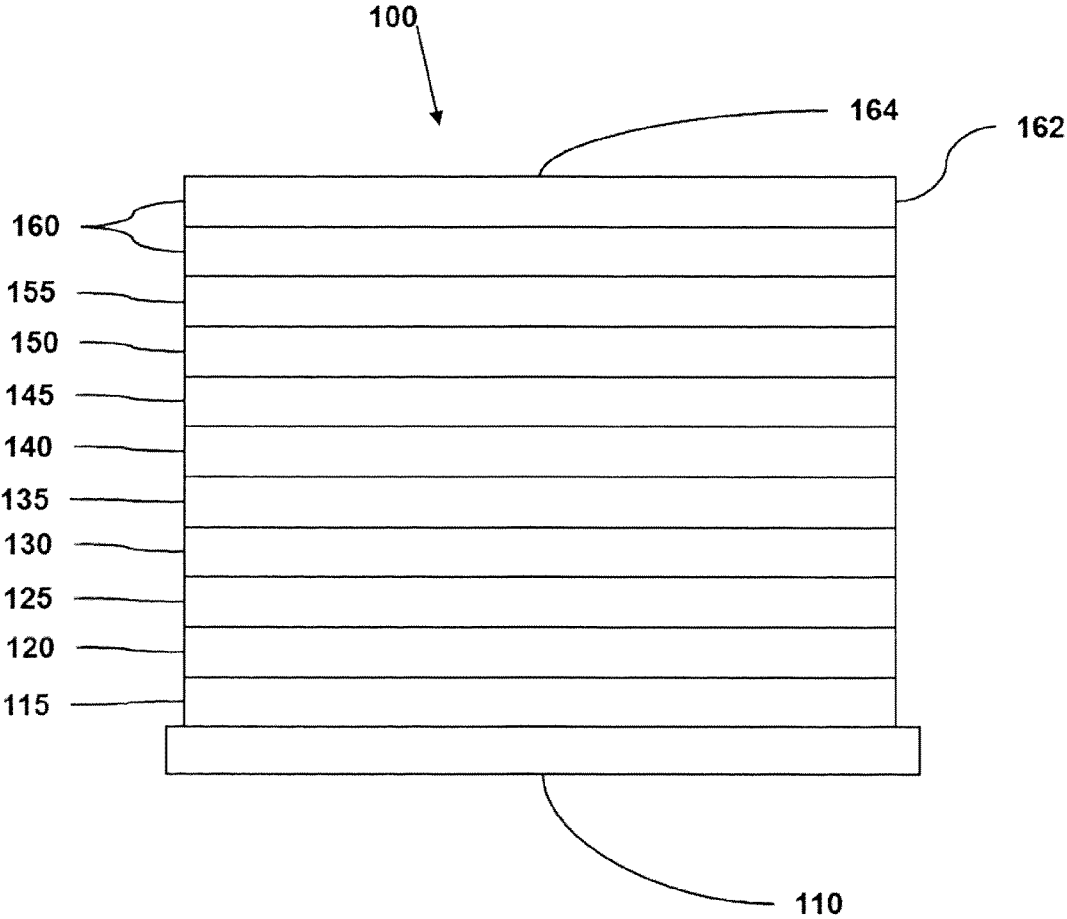


Figure 1

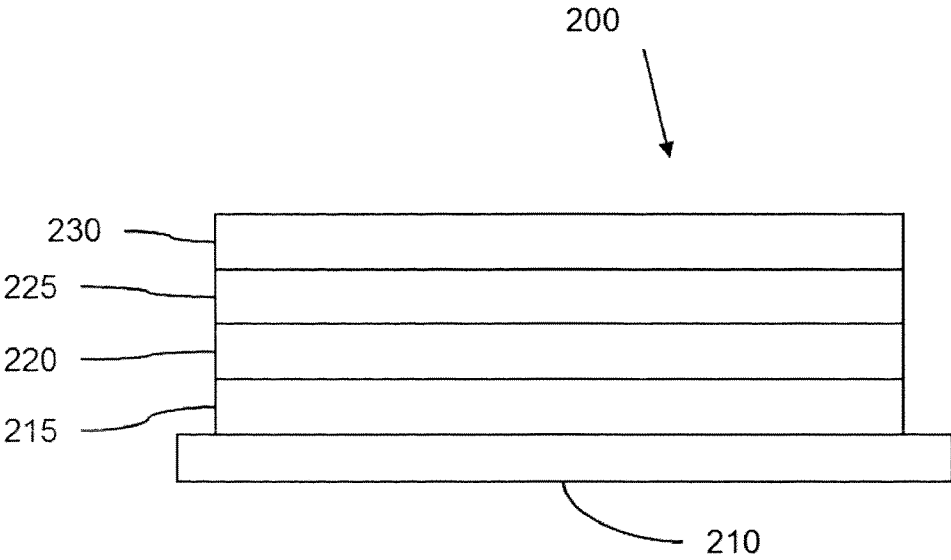


Figure 2

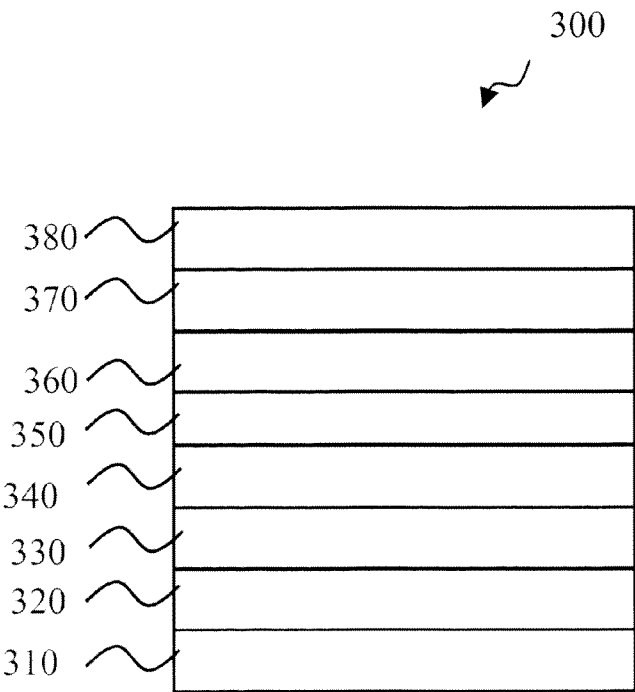


FIG. 3

INTERNATIONAL SEARCH REPORT

International application No
PCT/US2014/020899

A. CLASSIFICATION OF SUBJECT MATTER
INV. C09K11/06 H05B33/10 H05B33/14
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)
C09K H05B H01L

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, CHEM ABS Data, COMPENDEX, INSPEC, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
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X	WO 2010/111175 A1 (UNIVERSAL DISPLAY CORP [US]; XIA CHUANJUN [US]; KWONG RAYMOND [US]; LA) 30 September 2010 (2010-09-30) page 61 - page 65 -----	1-20
X	EP 2 468 731 A1 (TOSOH CORP [JP]; SAGAMI CHEMICAL RES INST [JP]) 27 June 2012 (2012-06-27) page 77 - page 81; example 23 -----	7,17,19



Further documents are listed in the continuation of Box C.



See patent family annex.

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"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

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Date of the actual completion of the international search

13 June 2014

Date of mailing of the international search report

25/06/2014

Name and mailing address of the ISA/

European Patent Office, P.B. 5818 Patentlaan 2
NL - 2280 HV Rijswijk
Tel. (+31-70) 340-2040,
Fax: (+31-70) 340-3016

Authorized officer

Doslik, Natasa

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No

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