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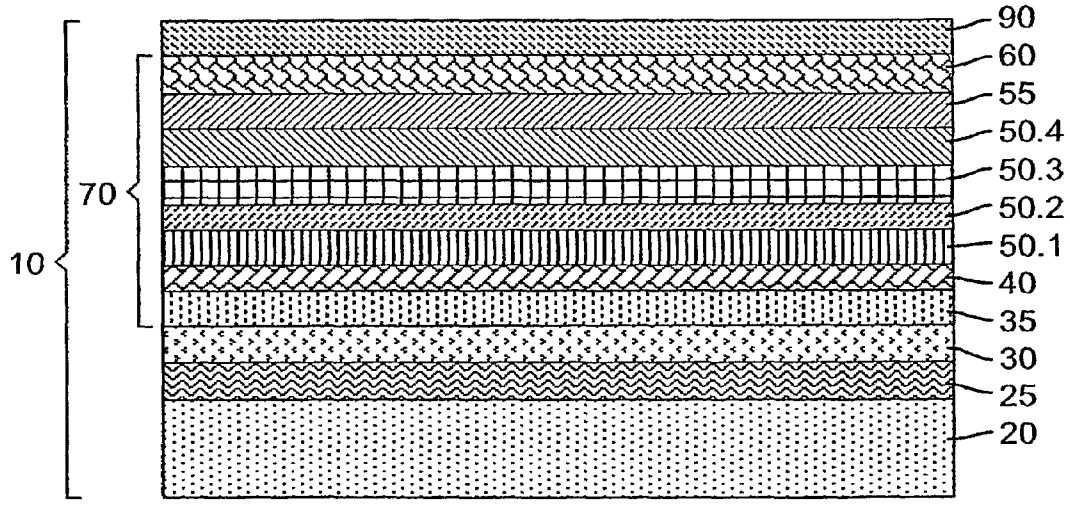
(54) **Title:** EFFICIENT WHITE-LIGHT OLED DISPLAY WITH FILTERS



(57) **Abstract:** A white light-emitting OLED device comprising: an anode and a cathode; at least four light-emitting layers provided between the anode and the cathode, wherein each of the four light-emitting layers produces a different emission spectrum when current passes between the anode and cathode, and such spectra combine to form white light; and wherein the four light-emitting layers include a red light-emitting layer, a yellow light-emitting layer, a blue light-emitting layer, and a green light-emitting layer, arranged such that: i) each of the light-emitting layers is in contact with at least one other light-emitting layer, ii) the blue light-emitting layer is in contact with the green light-emitting layer, and iii) the red light-emitting layer is in contact with only one other light-emitting layer.

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EFFICIENT WHITE-LIGHT OLED DISPLAY WITH FILTERS

FIELD OF THE INVENTION

The present invention relates to broadband light-producing OLED displays with color filters.

BACKGROUND OF THE INVENTION

An organic light-emitting diode device, also called an OLED, commonly includes an anode, a cathode, and an organic electroluminescent (EL) unit sandwiched between the anode and the cathode. The organic EL unit includes at least a hole-transporting layer (HTL), a light-emitting layer (LEL), and an electron-transporting layer (ETL). OLEDs are attractive because of their low drive voltage, high luminance, wide viewing-angle, and capability for full color displays and for other applications. Tang et al. described this multilayer OLED in their U.S. Patents 4,769,292 and 4,885,211.

OLEDs can emit different colors, such as red, green, blue, or white, depending on the emitting property of its LEL. Recently, there is an increasing demand for broadband OLEDs to be incorporated into various applications, such as a solid-state lighting source, color display, or a full color display. By broadband emission, it is meant that an OLED emits sufficiently broad light throughout the visible spectrum so that such light is used in conjunction with filters or color change modules to produce displays with at least two different colors or a full color display. In particular, there is a need for broadband-light-emitting OLEDs (or broadband OLEDs) where there is substantial emission in the red, green, and blue portions of the spectrum, i.e., a white light-emitting OLED (white OLED). The use of white OLEDs with color filters provides a simpler manufacturing process than an OLED having separately patterned red, green, and blue emitters. This can result in higher throughput, increased yield, and cost savings. White OLEDs have been reported in the prior art, such as reported by Kido et al. in *Applied Physics Letters*, **64**, 815 (1994), J. Shi et al. in U.S. Patent 5,683,823, Sato et al. in JP 07-142169, Deshpande et al. in *Applied Physics*

Letters, **75**, 888 (1999), and Tokito, et al. in *Applied Physics Letters*, **83**, 2459 (2003).

In order to achieve broadband emission from an OLED, more than one type of molecule has to be excited because each type of molecule only emits light with a relatively narrow spectrum under normal conditions. A light-emitting layer having a host material and one or more luminescent dopant(s) can achieve light emission from both the host and the dopant(s) resulting in a broadband emission in the visible spectrum if the energy transfer from the host material to the dopant(s) is incomplete. To achieve a white OLED having a single light-emitting layer, the concentrations of light-emitting dopants need to be carefully controlled. This produces manufacturing difficulties. A white OLED having two or more light-emitting layers can have better color as well as better luminance efficiency than a device with one light-emitting layer, and the variability tolerance for dopant concentration is higher. It has also been found that white OLEDs having two light-emitting layers are typically more stable than OLEDs having a single light-emitting layer. However, it is difficult to achieve light emission with strong intensity in the red, green, and blue portions of the spectrum. A white OLED with two light-emitting layers typically has two intensive emission peaks. It is known to use a third light-emitting layer to provide a third intensive emission peak, but such a three-layer structure shows diminished efficiency.

Recently, a tandem OLED structure (sometimes called a stacked OLED or cascaded a OLED) has been disclosed by Jones et al. in U.S. Patent 6,337,492, Tanaka et al. in U.S. Patent 6,107,734, Kido et al. in JP Patent Publication 2003/045676A and in U.S. Patent Publication 2003/0189401 A1, and Liao et al. in U.S. Patent 6,717,358 and U.S. Patent Application Publication 2003/0170491 A1. This tandem OLED is fabricated by stacking several individual OLED units vertically and driving the stack using a single power source. The advantage is that luminance efficiency, lifetime, or both are increased. However, the tandem structure increases the driving voltage approximately in proportion to the number of OLED units stacked together.

Matsumoto and Kido et al. reported in *SID 03 Digest*, 979 (2003) that a tandem white OLED is constructed by connecting a greenish blue EL unit and an orange EL unit in the device, and white light emission is achieved by driving this device with a single power source. Although luminance efficiency is increased, this tandem white OLED device has weaker green and red color components in the spectrum. In U.S. Patent Application Publication 2003/0170491 A1, Liao et al. describe a tandem white OLED structure by connecting a red EL unit, a green EL unit, and a blue EL unit in series within the device. When the tandem white OLED is driven by a single power source, white light emission is formed by spectral combination from the red, green, and blue EL units. Although color emission and luminance efficiency is improved, this tandem white OLED cannot be made with less than three EL units, implying that it requires a drive voltage at least 3 times as high as that of a conventional OLED.

A need exists for displays that are simple to make, but also have effective color gamut and high efficiency.

SUMMARY OF THE INVENTION

It is therefore an object of the present invention to produce an OLED display that is simple to make and has good color gamut and improved efficiency.

This object is achieved by a white light-emitting OLED comprising:

a) an anode and a cathode;

b) at least four light-emitting layers provided between the anode and the cathode, wherein each of the four light-emitting layers produces a different emission spectrum when current passes between the anode and cathode, and such spectra combine to form white light; and

c) wherein the four light-emitting layers include a red light-emitting layer, a yellow light-emitting layer, a blue light-emitting layer, and a green light-emitting layer, arranged such that:

i) each of the light-emitting layers is in contact with at least one other light-emitting layer,

ii) the blue light-emitting layer is in contact with the green light-emitting layer, and

iii) the red light-emitting layer is in contact with only one other light-emitting layer.

It is an advantage of the present invention that it provides for a device with improved color gamut and improved power efficiency, with lower voltage requirements, high stability, and better angular dependence.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 shows a cross-sectional view of an OLED device in accordance with this invention;

FIG. 2a to 2h show cross-sectional views of the embodiments of arrangements of the light-emitting layers in the OLED device in accordance with this invention;

FIG. 3 shows a cross-sectional view of an OLED display in accordance with this invention;

FIG. 4 shows a cross-sectional view of another OLED device in accordance with this invention;

FIG. 5 shows a comparison of the emission spectrum of a four-layer white-light-emitting OLED device according to this invention with the spectra of two- and three-layer white-light-emitting OLED devices; and

FIG. 6 shows a comparison of the emission spectrum of a four-layer white-light-emitting OLED device according to this invention with the emission spectrum of a four-layer white-light-emitting single-stack OLED device.

Since device feature dimensions such as layer thicknesses are frequently in sub-micrometer ranges, the drawings are scaled for ease of visualization rather than dimensional accuracy.

DETAILED DESCRIPTION OF THE INVENTION

The term "OLED device" is used in its art-recognized meaning of a display device comprising organic light-emitting diodes as pixels. It can mean a device having a single pixel. The term "OLED display" as used herein means an OLED device comprising a plurality of pixels, which can be of different colors. A color OLED device emits light of at least one color. The term "multicolor" is employed to describe a display panel that is capable of emitting light of a different hue in different areas. In particular, it is employed to describe a display panel that is capable of displaying images of different colors. These areas are not necessarily contiguous. The term "full color" is employed to describe multicolor display panels that are capable of emitting in the red, green, and blue regions of the visible spectrum and displaying images in any combination of hues. The red, green, and blue colors constitute the three primary colors from which all other colors can be generated by appropriate mixing. The term "hue" refers to the intensity profile of light emission within the visible spectrum, with different hues exhibiting visually discernible differences in color. The term "pixel" is employed in its art-recognized usage to designate an area of a display panel that is stimulated to emit light independently of other areas. It is recognized that in full color systems, several pixels of different colors will be used together to produce a wide range of colors, and a viewer can term such a group a single pixel. For the purposes of this discussion, such a group will be considered several different colored pixels.

In accordance with this disclosure, broadband emission is light that has significant components in multiple portions of the visible spectrum, for example, blue and green. Broadband emission can also include the situation where light is emitted in the red, green, and blue portions of the spectrum in order to produce white light. White light is that light that is perceived by a user as having a white color, or light that has an emission spectrum sufficient to be used in combination with color filters to produce a practical full color display. For low power consumption, it is often advantageous for the chromaticity of the white

light-emitting OLED to be close to CIE D_{65}, i.e., CIE x = 0.31 and CIE y = 0.33. This is particularly the case for so-called RGBW displays having red, green, blue, and white pixels. Although CIEx, CIEy coordinates of about 0.31, 0.33 are ideal in some circumstances; the actual coordinates can vary significantly and still be very useful. The term "white light-emitting" as used herein refers to a device that produces white light internally, even though part of such light may be removed by color filters before viewing.

Turning now to FIG. 1, there is shown a cross-sectional view of a pixel of a white-light-emitting OLED device **10** according to a first embodiment of the present invention. Such an OLED device can be incorporated into e.g. a display or an area lighting system. The OLED device **10** includes at a minimum a substrate **20**, an anode **30**, a cathode **90** spaced from anode **30**, and at least four light-emitting layers **50.1**, **50.2**, **50.3**, and **50.4** provided between anode **30** and cathode **90**. The four light-emitting layers of organic EL element **70** include a red light-emitting layer, a yellow light-emitting layer, a blue light-emitting layer, and a green light-emitting layer. The exact order of these layers will be discussed further below. Each of the light-emitting layers **50.1**, **50.2**, **50.3**, and **50.4** produces a different emission spectrum when current passes between anode **30** and cathode **90**. These emission spectra combine to form white light as shown by spectrum **130** of FIG. 5. For comparison, spectrum **110** shows the emission spectrum of a white-light-emitting OLED device that has two emitting layers: a blue-light-emitting layer and a yellow-light-emitting layer. Spectrum **120** shows the emission spectrum of a white-light-emitting OLED device that has three emitting layers: a red-light-emitting layer, a green-light-emitting layer, and a blue-light-emitting layer. Spectrum **110** is relatively weak in the green portion of the visible spectrum, so that a green-filtered pixel will need to be driven to a greater brightness. Spectrum **120** has weak emission in the yellow region, and will thus have low efficiency (in candelas/amp), especially when used in a white pixel. In contrast, spectrum **130** displays neither of these weaknesses, and has good emission across much of the visible spectrum.

OLED device **10** can further include other layers, e.g. hole-transporting layers **40**, **45** electron-transporting layers **55**, **65** hole-injecting layer **35**, electron-injecting layer **60**, and color filter **25**. These will be described further below.

An exciton formed by hole-electron recombination in the blue light-emitting layer can transfer to the green, yellow, or red light-emitting layers. An exciton in the green light-emitting layer can transfer to the yellow or red light-emitting layers, and an exciton in the yellow light-emitting layer can transfer to the red light-emitting layer. Therefore, it is important for the functioning of this invention that the light-emitting layers be arranged in an order that is energetically favorable. Such an order is achieved when the light-emitting layers are arranged such that: i) each of the light-emitting layers is in contact with at least one other light-emitting layer, ii) the blue light-emitting layer is in contact with the green light-emitting layer, and iii) the red light-emitting layer is in contact with only one other light-emitting layer. The following figures show the arrangements that meet these criteria. Turning now to FIG. 2a, there is shown a cross-sectional view of one embodiment of arrangement of the light-emitting layers in OLED device **10** fulfilling these requirements. This arrangement and the subsequent arrangements to be described can be used for any of the OLED devices and OLED displays described herein. In the arrangement of FIG. 2a, red light-emitting layer **50r** is formed closest to anode **30**, yellow light-emitting layer **50y** is in contact with red light-emitting layer **50r**, blue light-emitting layer **50b** is in contact with yellow light-emitting layer **50y**, and green light-emitting layer **50g** is in contact with blue light-emitting layer **50b**. This is an energetically favorable order. Excitons in blue light-emitting layer **50b** can move to green light-emitting layer **50g** or to yellow light-emitting layer **50y**. Excitons in yellow light-emitting layer **50y** can move to red light-emitting layer **50r**. Of course, excitons in any layer can cause emission of light from that layer, and by varying the thicknesses of the different layers, one skilled in the art can tune the device for the desired emission. Since in this particular embodiment, yellow light-emitting layer **50y** serves as both a light-

emitting layer and a layer for transporting excitons to red light-emitting layer **50r**, it is necessary that it be thinner than light-emitting layers commonly used in the art for OLED devices. Desirably, yellow light-emitting layer **50y** has a thickness greater than 0.5 nm and less than 5 nm. If yellow light-emitting layer **50y** is less than 0.5 nm, the emission from this layer is minimal and the device therefore would not show the beneficial efficiency increase. If yellow light-emitting layer **50y** is greater than 5 nm, very few excitons will reach red light-emitting layer **50r**, and therefore emission in the red region of the spectrum will be less than optimum.

Turning now to FIG. 2b, there is shown a cross-sectional view of another embodiment of arrangement of the light-emitting layers in OLED device **10** in accordance with this invention. In this arrangement, red light-emitting layer **50r** is formed closest to anode **30**, yellow light-emitting layer **50y** has a thickness greater than 0.5 nm and less than 5 nm and is in contact with red light-emitting layer **50r**, green light-emitting layer **50g** is in contact with yellow light-emitting layer **50y**, and blue light-emitting layer **50b** is in contact with green light-emitting layer **50g**. In this embodiment, green light-emitting layer **50g** serves as both an intermediate layer for transferring excitons and an emitting layer. Therefore, its thickness must be selected to balance the two functions, as was described in FIG. 2a for yellow light-emitting layer **50y**. For green light-emitting layer **50g** as an intermediate layer, it desirably has a thickness greater than 0.5 nm and less than 20 nm.

Turning now to FIG. 2c, there is shown a cross-sectional view of another embodiment of arrangement of the light-emitting layers in OLED device **10** in accordance with this invention. In this arrangement, red light-emitting layer **50r** is formed closest to anode **30**, blue light-emitting layer **50b** is in contact with red light-emitting layer **50r**, green light-emitting layer **50g** has a thickness greater than 0.5 nm and less than 20 nm and is in contact with blue light-emitting layer **50b**, and yellow light-emitting layer **50y** is in contact with green light-emitting layer **50g**.

Turning now to FIG. 2d, there is shown a cross-sectional view of another embodiment of arrangement of the light-emitting layers in OLED device **10** in accordance with this invention. In this arrangement, red light-emitting layer **50r** is formed closest to anode **30**, green light-emitting layer **50g** has a thickness greater than 0.5 nm and less than 20 nm and is in contact with red light-emitting layer **50r**, blue light-emitting layer **50b** is in contact with green light-emitting layer **50g**, and yellow light-emitting layer **50y** is in contact with blue light-emitting layer **50b**.

Turning now to FIG. 2e, there is shown a cross-sectional view of another embodiment of arrangement of the light-emitting layers in OLED device **10** in accordance with this invention. In this arrangement, yellow light-emitting layer **50y** is formed closest to anode **30**, blue light-emitting layer **50b** is in contact with yellow light-emitting layer **50y**, green light-emitting layer **50g** has a thickness greater than 0.5 nm and less than 20 nm and is in contact with blue light-emitting layer **50b**, and red light-emitting layer **50r** is in contact with green light-emitting layer **50g**.

Turning now to FIG. 2f, there is shown a cross-sectional view of another embodiment of arrangement of the light-emitting layers in OLED device **10** in accordance with this invention. In this arrangement, yellow light-emitting layer **50y** is formed closest to anode **30**, green light-emitting layer **50g** has a thickness greater than 0.5 nm and less than 20 nm and is in contact with yellow light-emitting layer **50y**, blue light-emitting layer **50b** is in contact with green light-emitting layer **50g**, and red light-emitting layer **50r** is in contact with blue light-emitting layer **50b**.

Turning now to FIG. 2g, there is shown a cross-sectional view of another embodiment of arrangement of the light-emitting layers in OLED device **10** in accordance with this invention. In this arrangement, green light-emitting layer **50g** is formed closest to anode **30**, blue light-emitting layer **50b** is in contact with green light-emitting layer **50g**, yellow light-emitting layer **50y** has a thickness greater than 0.5 nm and less than 5 nm and is in contact with blue light-emitting

layer **50b**, and red light-emitting layer **50r** is in contact with yellow light-emitting layer **50y**.

Turning now to FIG. 2h, there is shown a cross-sectional view of another embodiment of arrangement of the light-emitting layers in OLED device **10** in accordance with this invention. In this arrangement, blue light-emitting layer **50b** is formed closest to anode **30**, green light-emitting layer **50g** has a thickness of greater than 0.5 nm and less than 20 nm and is in contact with blue light-emitting layer **50b**, yellow light-emitting layer **50y** has a thickness greater than 0.5 nm and less than 5 nm and is in contact with green light-emitting layer **50g**, and red light-emitting layer **50r** is in contact with yellow light-emitting layer **50y**.

Turning now to FIG. 3, there is shown a cross-sectional view of an OLED display **15** according to another embodiment of this invention. This embodiment is similar to the previous embodiment, but it comprises an array of first, second, third, and fourth light-emitting pixels **5r**, **5g**, **5b**, and **5w**, respectively. Pixel **5r** is a red light-emitting pixel, pixel **5g** is a green light-emitting pixel, pixel **5b** is a blue light-emitting pixel, and pixel **5w** is a white light-emitting pixel. Each pixel has an anode (e.g. anodes **30r**, **30g**, **30b**, and **30w**), a cathode (e.g. cathode **90**, which in this embodiment is a common cathode shared by all pixels of the array), and at least four light-emitting layers **50.1**, **50.2**, **50.3**, and **50.4** provided between the anode and the cathode: a red light-emitting layer, a yellow light-emitting layer, a blue light-emitting layer, and a green light-emitting layer. Each of the light-emitting layers **50.1**, **50.2**, **50.3**, and **50.4** produces a different emission spectrum when current passes between the anode and the cathode. These emission spectra combine to form white light. The order of the light-emitting layers can be any of those described above in FIG. 2a through FIG. 2h, according to the criteria described above for OLED device **10**.

OLED display **15** further includes an array of at least three different color filters, e.g. **25r**, **25g**, and **25b**, in operative association with the first, second, and third light-emitting pixels **5r**, **5g**, and **5b**, respectively. Such filters are selected to receive white light to produce different colored light. OLED display

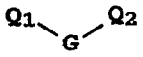
15 in this embodiment is bottom-emitting. Red color filter **25r** is in operative association with the first light-emitting pixel **5r** to receive white light **97** from light-emitting layers **50.1** through **50.4** and produce red light **97r**. Green color filter **25g** is in operative association with the second light-emitting pixel **5g** to receive white light **97** from the light-emitting layers and produce green light **97g**. Blue color filter **25b** is in operative association with the third light-emitting pixel **5b** to receive white light **97** from the light-emitting layers and produce blue light **97b**. Light-emitting pixel **5w** does not have a color filter, and therefore produces white light **97w** to a viewer.

OLED device layers that can be used in this invention have been well described in the art, and OLED device **10**, OLED display **15**, and other such devices described herein can include layers commonly used for such devices. A bottom electrode is formed over OLED substrate **20** and is most commonly configured as an anode **30**, although the practice of this invention is not limited to this configuration. Example conductors for this application include, but are not limited to, gold, iridium, molybdenum, palladium, platinum, aluminum or silver. Desired anode materials can be deposited by any suitable means such as evaporation, sputtering, chemical vapor deposition, or electrochemical means. Anode materials can be patterned using well-known photolithographic processes.

While not always necessary, it is often useful that a hole-transporting layer **40** be formed and disposed over the anode. Desired hole-transporting materials can be deposited by any suitable means such as evaporation, sputtering, chemical vapor deposition, electrochemical means, thermal transfer, or laser thermal transfer from a donor material. Hole-transporting materials useful in hole-transporting layers are well known to include compounds such as an aromatic tertiary amine, where the latter is understood to be a compound containing at least one trivalent nitrogen atom that is bonded only to carbon atoms, at least one of which is a member of an aromatic ring. In one form the aromatic tertiary amine can be an arylamine, such as a monoarylamine, diarylamine, triarylamine, or a polymeric arylamine. Exemplary monomeric triarylamines are illustrated by Klupfel et al. in U.S. Patent 3,180,730. Other suitable triarylamines substituted

with one or more vinyl radicals and/or comprising at least one active hydrogen-containing group are disclosed by Brantley et al. in U.S. Patents 3,567,450 and 3,658,520.

A more preferred class of aromatic tertiary amines are those which include at least two aromatic tertiary amine moieties as described in U.S. Patents 4,720,432 and 5,061,569. Such compounds include those represented by structural Formula A.

A 

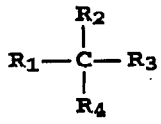
wherein:

Q_1 and Q_2 are independently selected aromatic tertiary amine moieties; and

G is a linking group such as an arylene, cycloalkylene, or alkylene group of a carbon to carbon bond.

In one embodiment, at least one of Q1 or Q2 contains a polycyclic fused ring structure, e.g., a naphthalene. When G is an aryl group, it is conveniently a phenylene, biphenylene, or naphthalene moiety.

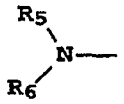
A useful class of triarylamines satisfying structural Formula A and containing two triarylamine moieties is represented by structural Formula B.

B 

where:

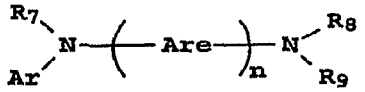
R_1 and R_2 each independently represent a hydrogen atom, an aryl group, or an alkyl group or R_1 and R_2 together represent the atoms completing a cycloalkyl group; and

R_3 and R_4 each independently represent an aryl group, which is in turn substituted with a diaryl substituted amino group, as indicated by structural Formula C.

C 

wherein R_5 and R_6 are independently selected aryl groups. In one embodiment, at least one of R_5 or R_6 contains a polycyclic fused ring structure, e.g., a naphthalene.

Another class of aromatic tertiary amines are the tetraaryldiamines. Desirable tetraaryldiamines include two diarylamino groups, such as indicated by Formula C, linked through an arylene group. Useful tetraaryldiamines include those represented by Formula D.

D 

wherein:

each Are is an independently selected arylene group, such as a phenylene or anthracene moiety;

n is an integer of from 1 to 4; and

Ar, R_7, R_8, and R_9 are independently selected aryl groups.

In a typical embodiment, at least one of Ar, R_7, R_8, and R_9 is a polycyclic fused ring structure, e.g., a naphthalene.

The various alkyl, alkylene, aryl, and arylene moieties of the foregoing structural Formulae A, B, C, and D can each in turn be substituted. Typical substituents include alkyl groups, alkoxy groups, aryl groups, aryloxy groups, and halogens such as fluoride, chloride, and bromide. The various alkyl and alkylene moieties typically contain from 1 to about 6 carbon atoms. The cycloalkyl moieties can contain from 3 to about 10 carbon atoms, but typically contain five, six, or seven carbon atoms--e.g., cyclopentyl, cyclohexyl, and cycloheptyl ring structures. The aryl and arylene moieties are usually phenyl and phenylene moieties.

The hole-transporting layer in an OLED device can be formed of a single or a mixture of aromatic tertiary amine compounds. Specifically, one can employ a triarylamine, such as a triarylamine satisfying the Formula B, in

combination with a tetraaryldiamine, such as indicated by Formula D. When a triarylamine is employed in combination with a tetraaryldiamine, the latter is positioned as a layer interposed between the triarylamine and the electron-injecting and transporting layer.

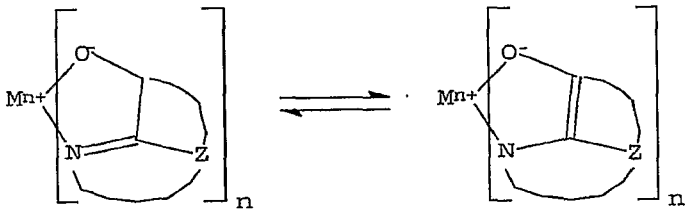
Another class of useful hole-transporting materials includes polycyclic aromatic compounds as described in EP 1 009 041. In addition, polymeric hole-transporting materials can be used such as poly(N-vinylcarbazole) (PVK), polythiophenes, polypyrrole, polyaniline, and copolymers such as poly(3,4-ethylenedioxythiophene)/poly(4-styrenesulfonate), also called PEDOT/PSS.

Light-emitting layers produce light in response to hole-electron recombination. The light-emitting layers are commonly disposed over the hole-transporting layer. Desired organic light-emitting materials can be deposited by any suitable means such as evaporation, sputtering, chemical vapor deposition, electrochemical means, or radiation thermal transfer from a donor material. Useful organic light-emitting materials are well known. As more fully described in U.S. Patents 4,769,292 and 5,935,721, the light-emitting layers of the OLED element comprise a luminescent or fluorescent material where electroluminescence is produced as a result of electron-hole pair recombination in this region. The light-emitting layers can be comprised of a single material, but more commonly include a host material doped with a guest compound or dopant where light emission comes primarily from the dopant. The dopant is selected to produce color light having a particular spectrum. The host materials in the light-emitting layers can be an electron-transporting material, as defined below, a hole-transporting material, as defined above, or another material that supports hole-electron recombination. The dopant is usually chosen from highly fluorescent dyes, but phosphorescent compounds, e.g., transition metal complexes as described in WO 98/55561, WO 00/18851, WO 00/57676, and WO 00/70655 are also useful. Dopants are typically coated as 0.01 to 10 % by weight into the host material. Host and emitting molecules known to be of use include, but are not limited to, those disclosed in U.S. Patents 4,768,292; 5,141,671; 5,150,006;

5,151,629; 5,294,870; 5,405,709; 5,484,922; 5,593,788; 5,645,948; 5,683,823; 5,755,999; 5,928,802; 5,935,720; 5,935,721; and 6,020,078.

Metal complexes of 8-hydroxyquinoline and similar derivatives (Formula E) constitute one class of useful host materials capable of supporting electroluminescence, and are particularly suitable for light emission of wavelengths longer than 500 nm, e.g., green, yellow, orange, and red.

E



wherein:

M represents a metal;

n is an integer of from 1 to 3; and

Z independently in each occurrence represents the atoms completing a nucleus having at least two fused aromatic rings.

From the foregoing it is apparent that the metal can be a monovalent, divalent, or trivalent metal. The metal can, for example, be an alkali metal, such as lithium, sodium, or potassium; an alkaline earth metal, such as magnesium or calcium; or an earth metal, such as boron or aluminum. Generally any monovalent, divalent, or trivalent metal known to be a useful chelating metal can be employed.

Z completes a heterocyclic nucleus containing at least two fused aromatic rings, at least one of which is an azole or azine ring. Additional rings, including both aliphatic and aromatic rings, can be fused with the two required rings, if required. To avoid adding molecular bulk without improving on function the number of ring atoms is usually maintained at 18 or less.

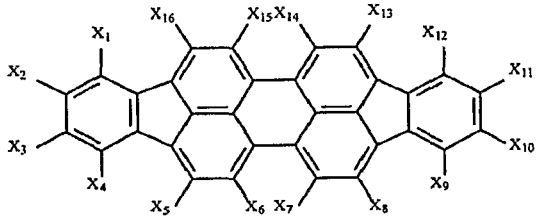
The host material in the light-emitting layers can be an anthracene derivative having hydrocarbon or substituted hydrocarbon substituents at the 9 and 10 positions. For example, derivatives of 9,10-di-(2-naphthyl)anthracene constitute one class of useful host materials capable of supporting

electroluminescence, and are particularly suitable for light emission of wavelengths longer than 400 nm, e.g., blue, green, yellow, orange or red.

Benzazole derivatives constitute another class of useful host materials capable of supporting electroluminescence, and are particularly suitable for light emission of wavelengths longer than 400 nm, e.g., blue, green, yellow, orange or red. An example of a useful benzazole is 2, 2', 2"-(1,3,5-phenylene)tris[1-phenyl-1H-benzimidazole].

The red-light-emitting compound can include a diindenoperylene compound of the following structure F:

F

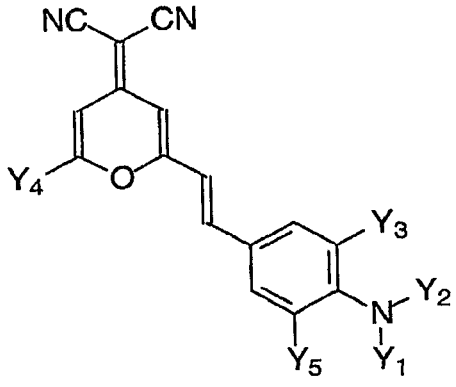


wherein:

X_1-X_{16} are independently selected as hydrogen or substituents that include alkyl groups of from 1 to 24 carbon atoms; aryl or substituted aryl groups of from 5 to 20 carbon atoms; hydrocarbon groups containing 4 to 24 carbon atoms that complete one or more fused aromatic rings or ring systems; or halogen, provided that the substituents are selected to provide an emission maximum between 560 nm and 640 nm.

Illustrative examples of useful red dopants of this class are shown by Hatwar et al. in US Publication No. 2005/0249972, the contents of which are incorporated by reference.

Other red dopants useful in the present invention belong to the DCM class of dyes represented by Formula G:



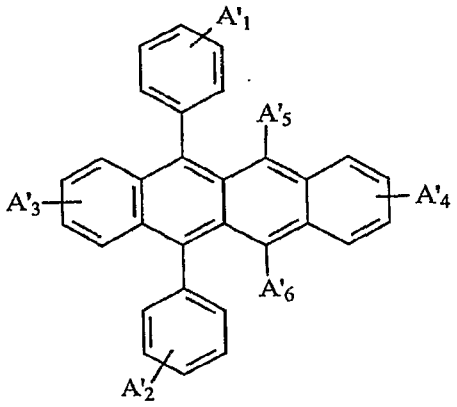
(Formula G)

wherein Y_1 - Y_5 represent one or more groups independently selected from: hydro, alkyl, substituted alkyl, aryl, or substituted aryl; Y_1 – Y_5 independently include acyclic groups or can be joined pairwise to form one or more fused rings; provided that Y_3 and Y_5 do not together form a fused ring.

In a useful and convenient embodiment that provides red luminescence, Y_1 - Y_5 are selected independently from: hydro, alkyl and aryl. Structures of particularly useful dopants of the DCM class are shown by Ricks et al. in U.S. Patent Publication No. 2005/0181232, the contents of which are incorporated by reference.

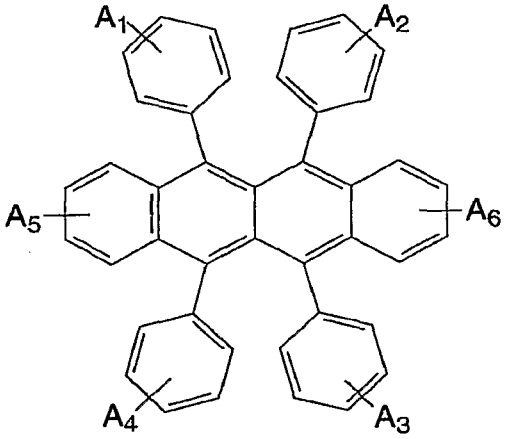
A light-emitting yellow dopant can include a compound of the following structures:

H1



or

H2



wherein A_1- A_6 and A'_1- A'_6 represent one or more substituents on each ring and where each substituent is individually selected from one of the following:

Category 1: hydrogen, or alkyl of from 1 to 24 carbon atoms;

Category 2: aryl or substituted aryl of from 5 to 20 carbon atoms;

Category 3: hydrocarbon containing 4 to 24 carbon atoms, completing a fused aromatic ring or ring system;

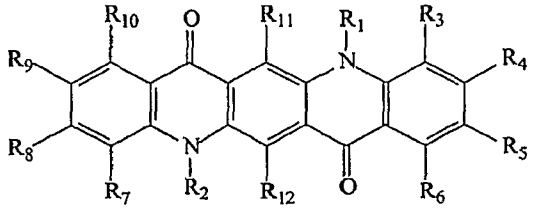
Category 4: heteroaryl or substituted heteroaryl of from 5 to 24 carbon atoms such as thiazolyl, furyl, thienyl, pyridyl, quinolinyl or other heterocyclic systems, which are bonded via a single bond, or complete a fused heteroaromatic ring system;

Category 5: alkoxylamino, alkylamino, or arylamino of from 1 to 24 carbon atoms; or

Category 6: fluoro, chloro, bromo or cyano.

Examples of particularly useful yellow dopants are shown by Ricks et al.

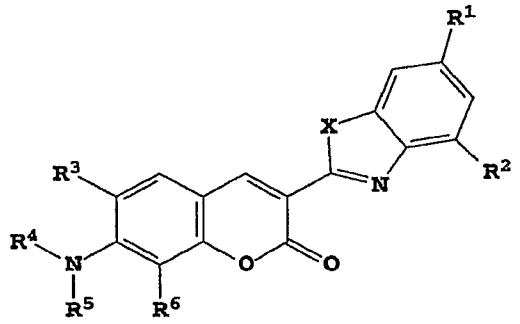
The green-light-emitting compound can include a quinacridone compound of the following structure:



J

wherein substituent groups R1 and R2 are independently alkyl, alkoxyl, aryl, or heteroaryl; and substituent groups R3 through R12 are independently hydrogen, alkyl, alkoxyl, halogen, aryl, or heteroaryl, and adjacent substituent groups R3 through R10 can optionally be connected to form one or more ring systems, including fused aromatic and fused heteroaromatic rings, provided that the substituents are selected to provide an emission maximum between 510 nm and 540 nm, and a full width at half maximum of 40 nm or less. Alkyl, alkoxyl, aryl, heteroaryl, fused aromatic ring and fused heteroaromatic ring substituent groups can be further substituted. Conveniently, R1 and R2 are aryl, and R2 through R12 are hydrogen, or substituent groups that are more electron withdrawing than methyl. Some examples of useful quinacridones include those disclosed in US 5,593,788 and in US2004/0001969A1.

The green-light-emitting compound can include a coumarin compound of the following structure:



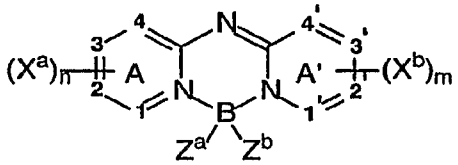
K

wherein X is O or S; R^1, R^2, R^3 and R^6 can individually be hydrogen, alkyl, or aryl; R^4 and R^5 can individually be alkyl or aryl; or where either R^3 and R^4, or R^5 and R^6, or both together represent the atoms completing a cycloalkyl group; provided that the substituents are selected to provide an emission maximum between 510 nm and 540 nm, and a full width at half maximum of 40 nm or less.

Examples of useful green dopants are disclosed by Hatwar et al. in U.S. Patent Publication No. 2005/0181232.

The blue-light-emitting dopant can include perylene or derivatives thereof, or a bis(azinyl)azene boron complex compound of the structure L:

L



wherein:

A and A' represent independent azine ring systems corresponding to 6-membered aromatic ring systems containing at least one nitrogen;

$(X^a)_n$ and $(X^b)_m$ represent one or more independently selected substituents and include acyclic substituents or are joined to form a ring fused to A or A';

m and n are independently 0 to 4;

Z^a and Z^b are independently selected substituents;

1, 2, 3, 4, 1', 2', 3', and 4' are independently selected as either carbon or nitrogen atoms; and

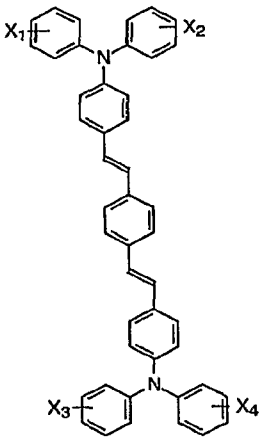
provided that X^a, X^b, Z^a, and Z^b, 1, 2, 3, 4, 1', 2', 3', and 4' are selected to provide blue luminescence.

Some examples of the above class of dopants are disclosed by Ricks et al.

Particularly useful blue dopants of the perylene class include perylene and tetra-t-butylperylene (TBP).

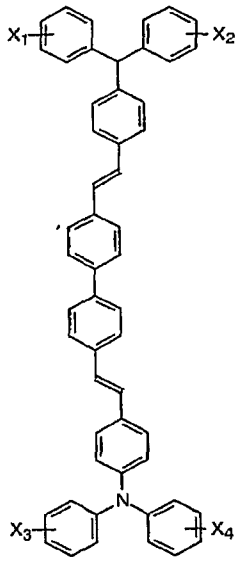
Another particularly useful class of blue dopants in this invention includes blue-emitting derivatives of such distyrylarenes as distyrylbenzene and distyrylbiphenyl, including compounds described in U.S. Patent 5,121,029. Among derivatives of distyrylarenes that provide blue luminescence, particularly useful are those substituted with diarylamino groups, also known as distyrylamines. Examples include bis[2-[4-[N,N-diarylamino]phenyl]vinyl]-benzenes of the general structure M1 shown below:

M1



and bis[2-[4-[N,N-diarylamino]phenyl]vinyl]biphenyls of the general structure M2 shown below:

M2



In Formulas M1 and M2, $X_1 - X_4$ can be the same or different, and individually represent one or more substituents such as alkyl, aryl, fused aryl, halo, or cyaNo. In a preferred embodiment, $X_1 - X_4$ are individually alkyl groups, each containing from one to about ten carbon atoms. A particularly preferred blue dopant of this class is disclosed by Ricks et al.

While not always necessary, it is often useful to include an electron-transporting layer **55** disposed over the light-emitting layers. Desired electron-transporting materials can be deposited by any suitable means such as evaporation, sputtering, chemical vapor deposition, electrochemical means, thermal transfer, or laser thermal transfer from a donor material. Preferred electron-transporting materials for use in the electron-transporting layer are metal chelated oxinoid compounds, including chelates of oxine itself (also commonly referred to as 8-quinolinol or 8-hydroxyquinoline). Such compounds help to inject and transport electrons and exhibit both high levels of performance and are readily fabricated in the form of thin films. Exemplary of contemplated oxinoid compounds are those satisfying structural Formula E, previously described.

Other electron-transporting materials include various butadiene derivatives as disclosed in U.S. Patent 4,356,429 and various heterocyclic optical

brighteners as described in U.S. Patent 4,539,507. Certain benzazoles are also useful electron-transporting materials. Other electron-transporting materials can be polymeric substances, e.g. polyphenylenevinylene derivatives, poly-para-phenylene derivatives, polyfluorene derivatives, polythiophenes, polyacetylenes, and other conductive polymeric organic materials known in the art.

An upper electrode most commonly configured as a cathode **90** is formed over the electron-transporting layer, or over the light-emitting layers if an electron-transporting layer is not used. If the device is top-emitting, the electrode must be transparent or nearly transparent. For such applications, metals must be thin (preferably less than 25 nm) or one must use transparent conductive oxides (e.g. indium-tin oxide, indium-zinc oxide), or a combination of these materials. Optically transparent cathodes have been described in more detail in U.S. Patent 5,776,623. Cathode materials can be deposited by evaporation, sputtering, or chemical vapor deposition. When needed, patterning can be achieved through many well known methods including, but not limited to, through-mask deposition, integral shadow masking as described in U.S. Patent 5,276,380 and EP 0 732 868, laser ablation, and selective chemical vapor deposition.

OLED device **10** can include other layers as well. For example, a hole-injecting layer **35** can be formed over the anode, as described in U.S. 4,720,432, U.S. 6,208,075, EP 0 891 121 A1, and EP 1 029 909 A1. An electron-injecting layer **60**, such as alkaline or alkaline earth metals, alkali halide salts, or alkaline or alkaline earth metal doped organic layers, can also be present between the cathode and the electron-transporting layer.

Turning now to FIG. 4, there is shown a cross-sectional view of a pixel of a tandem white-light-emitting OLED device **80** according to another embodiment of the present invention. Tandem OLED devices have previously been disclosed by Jones et al. in U.S. Patent 6,337,492, Tanaka et al. in U.S. Patent 6,107,734, Kido et al. in JP Patent Publication 2003/045676A and in U.S. Patent Publication 2003/0189401 A1, and Liao et al. in U.S. Patent 6,717,358 and U.S. Patent Application Publication 2003/0170491 A1. OLED device **80** includes

a substrate **20**, a spaced anode and cathode **90**, and at least two white light-emitting units **75** and **85** disposed between the electrodes. White light-emitting units **75** and **85** produce emission spectra corresponding to white light. Each white light-emitting unit has four light-emitting layers: light-emitting layers **50.1**, **50.2**, **50.3**, and **50.4** for white light-emitting unit **75**, and light-emitting layers **51.1**, **51.2**, **51.3**, and **51.4** for white light-emitting unit **85**. Each light-emitting unit includes a red light-emitting layer, a yellow light-emitting layer, a blue light-emitting layer, and a green light-emitting layer. Each of the light-emitting layers of a given white light-emitting unit produces a different emission spectrum when current passes between anode **30** and cathode **90**. These emission spectra combine to form white light. White light-emitting units **75** and **85** can have the structure of any of those described in FIG. 2a through FIG. 2h, according to the criteria described above for OLED device **10**. White light-emitting units **75** and **85** can have the same order of light-emitting layers, or can have different orders. For example, one embodiment of tandem OLED device **80** can have the structure wherein both white light-emitting units **75** and **85** have the same layer order, e.g. that of FIG. 2b. A different embodiment of tandem OLED device **80** can have the structure wherein white light-emitting unit **75** has a layer order of, e.g. that of FIG. 2a, while white light-emitting unit **85** has a different layer order, e.g. that of FIG. 2e. Further, the light-emitting layers used can be the same or different (e.g. white light-emitting units **75** and **85** can have red light-emitting layers of the same or different composition, etc.)

Tandem OLED device **80** further includes an intermediate connector **95** disposed between white light-emitting units **75** and **85**. The intermediate connector provides effective carrier injection into the adjacent EL units. Metals, metal compounds, or other inorganic compounds are effective for carrier injection. However, such materials often have low resistivity, which can result in pixel crosstalk. Also, the optical transparency of the layers constituting the intermediate connector should be as high as possible to permit for radiation produced in the EL units to exit the device. Therefore, it is often preferred to use mainly organic materials in the intermediate connector. Intermediate connector **95**

and materials used in its construction have been described in detail by Hatwar et al. in U.S. Patent Application 11/170,681. Some further non-limiting examples of intermediate connectors are described in U.S. Patents 6,717,358 and 6,872,472, and U.S. Patent Application Publication 2004/0227460 A1.

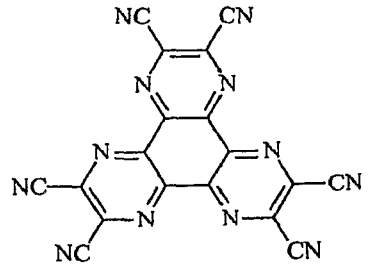
Turning now to FIG. 6, there is shown an emission spectrum **150** of a tandem OLED device as shown in FIG. 4. For comparison, spectrum **140** shows a single-stack OLED device with four light-emitting layers as described herein. While both have good emission across much of the visible spectrum the tandem OLED device shows greater radiance.

The invention and its advantages can be better appreciated by the following comparative examples. The layers described as vacuum-deposited were deposited by evaporation from heated boats under a vacuum of approximately 10^{-6} Torr. After deposition of the OLED layers each device was then transferred to a dry box for encapsulation. The OLED has an emission area of 10 mm^2. The devices were tested by applying a current of 20 mA/cm^2 across electrodes. The performance of the devices is given in Table 1. The color gamut for each device was calculated relative to the aim NTSC red, green, and blue color coordinates as measured in CIEx,y space.

Example 1 (Comparative two-layer)

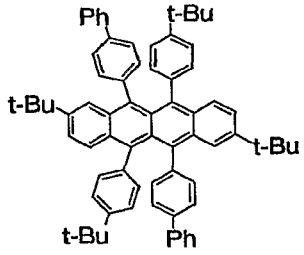
A comparative color OLED display was constructed in the following manner:

1. A clean glass substrate was deposited by sputtering with indium tin oxide (ITO) to form a transparent electrode of 85 nm thickness.
2. The above-prepared ITO surface was treated with a plasma oxygen etch.
3. The above-prepared substrate was further treated by vacuum-depositing a 10 nm layer of hexacyanohexaazatriphenylene (CHATP) as a hole-injecting layer (HIL).



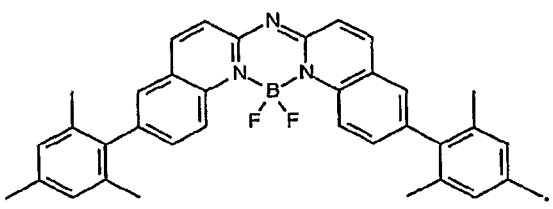
CHATP

4. The above-prepared substrate was further treated by vacuum-depositing a 10 nm layer of 4,4'-bis[N-(1-naphthyl)-N-phenylamino]biphenyl (NPB) as a hole-transporting layer (HTL).
5. The above-prepared substrate was further treated by vacuum-depositing a 20 nm yellow light-emitting layer including 14 nm NPB (as host) and 6 nm 9,10-bis(2-naphthyl)anthracene (ADN) as a stabilizer with 2% yellow-orange emitting dopant diphenyltetra-t-butylrubrene (PTBR).



PTBR

6. The above-prepared substrate was further treated by vacuum-depositing a 20 nm blue light-emitting layer including 18.4 nm 9-(2-naphthyl)-10-(4-biphenyl)anthracene (BNA) host and 1.4 nm NPB cohost with 1% BEP as blue-emitting dopant.



BEP

7. A 40 nm mixed electron-transporting layer was vacuum-deposited, including 200 nm 4,7-diphenyl-1,10-phenanthroline (also known as bathophen or Bphen), 200 nm tris(8-quinolinolato)aluminum (III) (ALQ) as co-host, with 2 % Li metal.
8. A 100 nm layer of aluminum was evaporatively deposited onto the substrate to form a cathode layer.

Example 2 (Comparative three-layer)

A comparative color OLED display was constructed in the following manner:

1. A clean glass substrate was deposited by sputtering with ITO to form a transparent electrode of 60 nm thickness.
2. The above-prepared ITO surface was treated with a plasma oxygen etch.
3. The above-prepared substrate was further treated by vacuum-depositing a 10 nm layer of CHATP as a hole-injecting layer (HIL).
4. The above-prepared substrate was further treated by vacuum-depositing a 10 nm layer of NPB as a hole-transporting layer (HTL).
5. The above-prepared substrate was further treated by vacuum-depositing a 20 nm red light-emitting layer including 14 nm of NPB and 6 nm BNA as a stabilizer doped with 0.5 % dibenzo{[*f,f'*]-4,4'7,7'-tetraphenyl]diindeno-[1,2,3-*cd*:1',2',3'-*lm*]perylene (TPDBP) as a red emitting dopant.
6. The above-prepared substrate was further treated by vacuum-depositing a 15 nm blue light-emitting layer including 14 nm BNA host and 1 nm NPB cohost with 1% BEP as blue-emitting dopant.

7. The above-prepared substrate was further treated by vacuum-depositing a 15 nm green light-emitting layer including 14 nm BNA, 1 nm NPB, and 0.5% diphenylquinacridone (DPQ) as green emitting dopant.
8. A 40 nm mixed electron-transporting layer was vacuum-deposited, including 200 nm Bphen, 200 nm tris(8-quinolinolato)aluminum (III) (ALQ) as co-host, with 2 % Li metal.
9. A 100 nm layer of aluminum was evaporatively deposited onto the substrate to form a cathode layer.

Example 3 (Inventive)

An inventive color OLED display was constructed in the following manner:

1. A clean glass substrate was deposited by sputtering with ITO to form a transparent electrode of 60 nm thickness.
2. The above-prepared ITO surface was treated with a plasma oxygen etch.
3. The above-prepared substrate was further treated by vacuum-depositing a 10 nm layer of CHATP as a hole-injecting layer (HIL).
4. The above-prepared substrate was further treated by vacuum-depositing a 10 nm layer of NPB as a hole-transporting layer (HTL).
5. The above-prepared substrate was further treated by vacuum-depositing a 18 nm red light-emitting layer including 12.6 nm of NPB and 5.4 nm BNA as a stabilizer doped with 0.5 % TPDBP as a red emitting dopant.
6. The above-prepared substrate was further treated by vacuum-depositing a 2 nm yellow light-emitting layer including 1.4 nm NPB (as host) and 0.6 nm ADN as a stabilizer with 3% yellow-orange emitting dopant PTBR.

7. The above-prepared substrate was further treated by vacuum-depositing a 15 nm blue light-emitting layer including 14 nm BNA host and 1 nm NPB cohost with 1% BEP as blue-emitting dopant.
8. The above-prepared substrate was further treated by vacuum-depositing a 15 nm green light-emitting layer including 14 nm BNA, 1 nm NPB, and 0.5% DPQ as green emitting dopant.
9. A 40 nm mixed electron-transporting layer was vacuum-deposited, including 200 nm Bphen, 200 nm ALQ as co-host, with 2 % Li metal.
10. A 100 nm layer of aluminum was evaporatively deposited onto the substrate to form a cathode layer.

Example 4 (Inventive)

An inventive color OLED display was constructed in the following manner:

1. A clean glass substrate was deposited by sputtering with ITO to form a transparent electrode of 60 nm thickness.
2. The above-prepared ITO surface was treated with a plasma oxygen etch.
3. The above-prepared substrate was further treated by vacuum-depositing a 10 nm layer of CHATP as a hole-injecting layer (HIL).
4. The above-prepared substrate was further treated by vacuum-depositing a 10 nm layer of NPB as a hole-transporting layer (HTL).
5. The above-prepared substrate was further treated by vacuum-depositing a 16 nm red light-emitting layer including 11.2 nm of NPB and 4.8 nm BNA as a stabilizer doped with 0.5 % TPDBP as a red emitting dopant.

6. The above-prepared substrate was further treated by vacuum-depositing a 4 nm yellow light-emitting layer including 2.8 nm NPB (as host) and 1.2 nm ADN as a stabilizer with 3% yellow-orange emitting dopant PTBR.
7. The above-prepared substrate was further treated by vacuum-depositing a 15 nm blue light-emitting layer including 14 nm BNA host and 1 nm NPB cohost with 1% BEP as blue-emitting dopant.
8. The above-prepared substrate was further treated by vacuum-depositing a 15 nm green light-emitting layer including 14 nm BNA, 1 nm NPB, and 0.5% DPQ as green emitting dopant.
9. A 40 nm mixed electron-transporting layer was vacuum-deposited, including 200 nm Bphen, 200 nm ALQ as co-host, with 2 % Li metal.
10. A 100 nm layer of aluminum was evaporatively deposited onto the substrate to form a cathode layer.

Example 5 (Inventive)

An inventive color OLED display was constructed in the following manner:

1. A clean glass substrate was deposited by sputtering with ITO to form a transparent electrode of 60 nm thickness.
2. The above-prepared ITO surface was treated with a plasma oxygen etch.
3. The above-prepared substrate was further treated by vacuum-depositing a 10 nm layer of CHATP as a hole-injecting layer (HIL).
4. The above-prepared substrate was further treated by vacuum-depositing a 21 nm red light-emitting layer including 14 nm of NPB and 6 nm BNA as a stabilizer doped with 0.5 % TPDBP as a red emitting dopant.

5. The above-prepared substrate was further treated by vacuum-depositing a 3 nm yellow light-emitting layer including 2 nm NPB (as host) and 1 nm ADN as a stabilizer with 2% yellow-orange emitting dopant PTBR.
6. The above-prepared substrate was further treated by vacuum-depositing a 15 nm blue light-emitting layer including 14.5 nm BNA host and 0.5 nm NPB cohost with 1% BEP as blue-emitting dopant.
7. The above-prepared substrate was further treated by vacuum-depositing a 15 nm green light-emitting layer including 14.5 nm BNA, 0.5 nm NPB, and 0.5% DPQ as green emitting dopant.
8. A 40 nm mixed electron-transporting layer was vacuum-deposited, including 200 nm Bphen, 200 nm ALQ as co-host, with 2 % Li metal.
9. A 100 nm layer of aluminum was evaporatively deposited onto the substrate to form a cathode layer.

Example 6 (Inventive Tandem Device)

An inventive color OLED display was constructed in the following manner:

1. A clean glass substrate was deposited by sputtering with ITO to form a transparent electrode of 60 nm thickness.
2. The above-prepared ITO surface was treated with a plasma oxygen etch.
3. The above-prepared substrate was further treated by vacuum-depositing a 10 nm layer of CHATP as a hole-injecting layer (HIL).
4. The above-prepared substrate was further treated by vacuum-depositing a 21 nm red light-emitting layer including 14 nm of NPB and 6 nm BNA as a stabilizer doped with 0.5 % TPDBP as a red emitting dopant.

5. The above-prepared substrate was further treated by vacuum-depositing a 3 nm yellow light-emitting layer including 2 nm NPB (as host) and 1 nm ADN as a stabilizer with 2% yellow-orange emitting dopant PTBR.
6. The above-prepared substrate was further treated by vacuum-depositing a 15 nm blue light-emitting layer including 14.5 nm BNA host and 0.5 nm NPB cohost with 1% BEP as blue-emitting dopant.
7. The above-prepared substrate was further treated by vacuum-depositing a 15 nm green light-emitting layer including 14.5 nm BNA, 0.5 nm NPB, and 0.5% DPQ as green emitting dopant.
8. A 40 nm n-type doped organic layer was vacuum-deposited, including 200 nm Bphen, 200 nm ALQ as co-host, and 2 % Li metal.
9. The above-prepared substrate was further treated by vacuum-depositing a 10 nm layer of CHATP as a p-type doped organic layer (HIL).
10. The above-prepared substrate was further treated by vacuum-depositing a 30 nm layer of NPB as a hole-transporting layer (HTL).
11. The above-prepared substrate was further treated by vacuum-depositing a 21 nm red light-emitting layer including 14 nm of NPB and 6 nm BNA as a stabilizer doped with 0.5 % TPDBP as a red emitting dopant.
12. The above-prepared substrate was further treated by vacuum-depositing a 3 nm yellow light-emitting layer including 2 nm NPB (as host) and 1 nm ADN as a stabilizer with 2% yellow-orange emitting dopant PTBR.
13. The above-prepared substrate was further treated by vacuum-depositing a 15 nm blue light-emitting layer

including 14.5 nm BNA host and 0.5 nm NPB cohost with 1% BEP as blue-emitting dopant.

14. The above-prepared substrate was further treated by vacuum-depositing a 15 nm green light-emitting layer including 14.5 nm BNA, 0.5 nm NPB, and 0.5% DPQ as green emitting dopant.
15. A 40 nm mixed electron-transporting layer was vacuum-deposited, including 200 nm Bphen, 200 nm ALQ as co-host, with 2 % Li metal.
16. A 100 nm layer of aluminum was evaporatively deposited onto the substrate to form a cathode layer.

The results of testing these examples are shown in Table 1, below. Comparative Examples 1 and 2 show that it is difficult to achieve both efficiency and effective color gamut. Example 1 has good efficiency but low color gamut. Example 2 has effective color gamut, but both luminance and power efficiencies are degraded relative to Example 1. In addition, Example 2 is an example of a broadband that is far from D65 white.

In the present invention, improved efficiency, white point, and color gamut are achieved by a four-layer emitting structure, including red-, yellow-, green-, and blue-light-emitting layers, as shown by Examples 3 to 5. Further improvements in efficiency are possible by using this structure in a tandem device, as in Example 6.

Table 1 - Device data measured at 20 mA/cm^2

Device #			Voltage	Lum Efficiency (cd/A)	Power Efficiency (W/A)	CIEx	CIEy	lm/W	QE%	Room Temp Fade Stability @80mA/cm^2 (hrs to 50%)	Color Gamut: NTSC ratio (%)
Example 1 (Comparative)	2-layer white		3.7	11.4	0.106	0.357	0.357	9.7	4.7	1000	50
Example 2 (Comparative)	3-layer white		4.5	6.1	0.079	0.240	0.285	4.3	3.3	800	75
Example 3 (Inventive)	4-layer white	2 nm yellow layer	4.5	8.5	0.086	0.317	0.358	6.0	3.8	1045	71
Example 4 (Inventive)	4-layer white	4 nm yellow layer	4.3	9.5	0.091	0.323	0.369	6.9	4.0	896	71
Example 5 (Inventive)	4-layer white	3 nm yellow layer	4.5	9.8	0.099	0.316	0.344	6.9	4.0	700	70
Example 6 (Inventive)	4-layer white	2-stack tandem, 3 nm yellow	8.7	17.5	0.175	0.327	0.366	6.3	7.7	562	70

PARTS LIST

5r	pixel
5g	pixel
5b	pixel
5w	pixel
10	OLED device
15	OLED display
20	substrate
25	color filter
25r	red color filter
25g	green color filter
25b	blue color filter
30	anode
30r	anode
30g	anode
30b	anode
30w	anode
35	hole-injecting layer
40	hole-transporting layer
45	hole-transporting layer
50.1	light-emitting layer
50.2	light-emitting layer
50.3	light-emitting layer
50.4	light-emitting layer
50r	red light-emitting layer
50y	yellow light-emitting layer
50b	blue light-emitting layer
50g	green light-emitting layer
51.1	light-emitting layer
51.2	light-emitting layer

51.3	light-emitting layer
51.4	light-emitting layer
55	electron-transporting layer
60	electron-injecting layer
65	electron-transporting layer
70	organic EL element
75	white light-emitting unit
80	OLED device
85	white light-emitting unit
90	cathode
95	intermediate connector
97	white light
97r	red light
97g	green light
97b	blue light
97w	white light
110	spectrum
120	spectrum
130	spectrum
140	spectrum
150	spectrum

CLAIMS:

1. A white light-emitting OLED device comprising:

a) an anode and a cathode;

b) at least four light-emitting layers provided between the anode and the cathode, wherein each of the four light-emitting layers produces a different emission spectrum when current passes between the anode and cathode, and such spectra combine to form white light; and

c) wherein the four light-emitting layers include a red light-emitting layer, a yellow light-emitting layer, a blue light-emitting layer, and a green light-emitting layer, arranged such that:

i) each of the light-emitting layers is in contact with at least one other light-emitting layer,

ii) the blue light-emitting layer is in contact with the green light-emitting layer, and

iii) the red light-emitting layer is in contact with only one other light-emitting layer.

2. The white light-emitting OLED device of claim 1 wherein the red light-emitting layer is formed closest to the anode, the yellow light-emitting layer has a thickness greater than 0.5 nm and less than 5 nm and is in contact with the red light-emitting layer, the blue light-emitting layer is in contact with the yellow light-emitting layer, and the green light-emitting layer is in contact with the blue light-emitting layer.

3. The white light-emitting OLED device of claim 1 wherein the red light-emitting layer is formed closest to the anode, the yellow light-emitting layer has a thickness greater than 0.5 nm and less than 5 nm and is in contact with the red light-emitting layer, the green light-emitting layer has a thickness greater than 0.5 nm and less than 20 nm and is in contact with the

yellow light-emitting layer, and the blue light-emitting layer is in contact with the green light-emitting layer.

4. The white light-emitting OLED device of claim 1 wherein the red light-emitting layer is formed closest to the anode, the blue light-emitting layer is in contact with the red light-emitting layer, the green light-emitting layer has a thickness greater than 0.5 nm and less than 20 nm and is in contact with the blue light-emitting layer, and the yellow light-emitting layer is in contact with the green light-emitting layer.

5. The white light-emitting OLED device of claim 1 wherein the red light-emitting layer is formed closest to the anode, the green light-emitting layer has a thickness greater than 0.5 nm and less than 20 nm and is in contact with the red light-emitting layer, the blue light-emitting layer is in contact with the green light-emitting layer, and the yellow light-emitting layer is in contact with the blue light-emitting layer.

6. The white light-emitting OLED device of claim 1 wherein the yellow light-emitting layer is formed closest to the anode, the blue light-emitting layer is in contact with the yellow light-emitting layer, the green light-emitting layer has a thickness greater than 0.5 nm and less than 20 nm and is in contact with the blue light-emitting layer, and the red light-emitting layer is in contact with the green light-emitting layer.

7. The white light-emitting OLED device of claim 1 wherein the yellow light-emitting layer is formed closest to the anode, the green light-emitting layer has a thickness greater than 0.5 nm and less than 20 nm and is in contact with the yellow light-emitting layer, the blue light-emitting layer is in contact with the green light-emitting layer, and the red light-emitting layer is in contact with the blue light-emitting layer.

8. The white light-emitting OLED device of claim 1 wherein the green light-emitting layer is formed closest to the anode, the blue light-emitting layer is in contact with the green light-emitting layer, the yellow light-emitting layer has a thickness greater than 0.5 nm and less than 5 nm and is in contact with the blue light-emitting layer, and the red light-emitting layer is in contact with the yellow light-emitting layer.

9. The white light-emitting OLED device of claim 1 wherein the blue light-emitting layer is formed closest to the anode, the green light-emitting layer has a thickness greater than 0.5 nm and less than 20 nm and is in contact with the blue light-emitting layer, the yellow light-emitting layer has a thickness greater than 0.5 nm and less than 5 nm and is in contact with the green light-emitting layer, and the red light-emitting layer is in contact with the yellow light-emitting layer.

10. A white light-emitting OLED display comprising:

a) an array of first, second, third, and fourth light-emitting pixels, each pixel having an anode, a cathode, and at least four light-emitting layers provided between the anode and the cathode, wherein each of the four light-emitting layers produces a different emission spectrum when current passes between the anode and cathode;

b) wherein the four light-emitting layers include a red light-emitting layer, a yellow light-emitting layer, a blue light-emitting layer, and a green light-emitting layer, arranged such that:

i) each of the light-emitting layers is in contact with at least one other light-emitting layer,

ii) the blue light-emitting layer is in contact with the green light-emitting layer, and

iii) the red light-emitting layer is in contact with only one other light-emitting layer; and

c) an array of at least three different color filters in operative association with the first, second, and third light-emitting pixels, such filters being selected to receive white light to produce different colored light.

11. The white light-emitting OLED device of claim 10 wherein the red light-emitting layer is formed closest to the anode, the yellow light-emitting layer has a thickness greater than 0.5 nm and less than 5 nm and is in contact with the red light-emitting layer, the blue light-emitting layer is in contact with the yellow light-emitting layer, and the green light-emitting layer is in contact with the blue light-emitting layer.

12. The white light-emitting OLED device of claim 10 wherein the red light-emitting layer is formed closest to the anode, the yellow light-emitting layer has a thickness greater than 0.5 nm and less than 5 nm and is in contact with the red light-emitting layer, the green light-emitting layer has a thickness greater than 0.5 nm and less than 20 nm and is in contact with the yellow light-emitting layer, and the blue light-emitting layer is in contact with the green light-emitting layer.

13. The white light-emitting OLED device of claim 10 wherein the red light-emitting layer is formed closest to the anode, the blue light-emitting layer is in contact with the red light-emitting layer, the green light-emitting layer has a thickness greater than 0.5 nm and less than 20 nm and is in contact with the blue light-emitting layer, and the yellow light-emitting layer is in contact with the green light-emitting layer.

14. The white light-emitting OLED device of claim 10 wherein the red light-emitting layer is formed closest to the anode, the green light-emitting layer has a thickness greater than 0.5 nm and less than 20 nm and is in contact

with the red light-emitting layer, the blue light-emitting layer is in contact with the green light-emitting layer, and the yellow light-emitting layer is in contact with the blue light-emitting layer.

15. The white light-emitting OLED device of claim 10 wherein the yellow light-emitting layer is formed closest to the anode, the blue light-emitting layer is in contact with the yellow light-emitting layer, the green light-emitting layer has a thickness greater than 0.5 nm and less than 20 nm and is in contact with the blue light-emitting layer, and the red light-emitting layer is in contact with the green light-emitting layer.

16. The white light-emitting OLED device of claim 10 wherein the yellow light-emitting layer is formed closest to the anode, the green light-emitting layer has a thickness greater than 0.5 nm and less than 20 nm and is in contact with the yellow light-emitting layer, the blue light-emitting layer is in contact with the green light-emitting layer, and the red light-emitting layer is in contact with the blue light-emitting layer.

17. The white light-emitting OLED device of claim 10 wherein the green light-emitting layer is formed closest to the anode, the blue light-emitting layer is in contact with the green light-emitting layer, the yellow light-emitting layer has a thickness greater than 0.5 nm and less than 5 nm and is in contact with the blue light-emitting layer, and the red light-emitting layer is in contact with the yellow light-emitting layer.

18. The white light-emitting OLED device of claim 10 wherein the blue light-emitting layer is formed closest to the anode, the green light-emitting layer has a thickness greater than 0.5 nm and less than 20 nm and is in contact with the blue light-emitting layer, the yellow light-emitting layer has a

thickness greater than 0.5 nm and less than 5 nm and is in contact with the green light-emitting layer, and the red light-emitting layer is in contact with the yellow light-emitting layer.

19. The white light-emitting OLED display of claim 10 wherein all the pixels of the array share a common cathode.

20. A tandem white light-emitting OLED device comprising:

a) a spaced anode and cathode;

b) at least two white light-emitting units that are disposed between the electrodes and that produce emission spectra corresponding to white light and each white light-emitting unit having four light-emitting layers including a red light-emitting layer, a yellow light-emitting layer, a blue light-emitting layer, and a green light-emitting layer, arranged such that:

i) each of the light-emitting layers of a white light-emitting unit is in contact with at least one other light-emitting layer of that unit,

ii) the blue light-emitting layer of a white light-emitting unit is in contact with the green light-emitting layer of that unit, and

iii) the red light-emitting layer of a white light-emitting unit is in contact with only one other light-emitting layer of that unit; and

c) an intermediate connector disposed between the white light-emitting units.

21. The tandem white light-emitting OLED device of claim 20 wherein at least one of the white light-emitting units has the structure comprising: the red light-emitting layer being formed closest to the anode, the yellow light-emitting layer having a thickness greater than 0.5 nm and less than 5 nm and being in contact with the red light-emitting layer, the blue light-emitting layer being in contact with the yellow light-emitting layer, and the green light-emitting layer being in contact with the blue light-emitting layer.

22. The tandem white light-emitting OLED device of claim 20 wherein at least one of the white light-emitting units has the structure comprising: the red light-emitting layer being formed closest to the anode, the yellow light-emitting layer having a thickness greater than 0.5 nm and less than 5 nm and being in contact with the red light-emitting layer, the green light-emitting layer having a thickness greater than 0.5 nm and less than 20 nm and being in contact with the yellow light-emitting layer, and the blue light-emitting layer being in contact with the green light-emitting layer.

23. The tandem white light-emitting OLED device of claim 20 wherein at least one of the white light-emitting units has the structure comprising: the red light-emitting layer being formed closest to the anode, the blue light-emitting layer being in contact with the red light-emitting layer, the green light-emitting layer having a thickness greater than 0.5 nm and less than 20 nm and being in contact with the blue light-emitting layer, and the yellow light-emitting layer being in contact with the green light-emitting layer.

24. The tandem white light-emitting OLED device of claim 20 wherein at least one of the white light-emitting units has the structure comprising: the red light-emitting layer being formed closest to the anode, the green light-emitting layer having a thickness greater than 0.5 nm and less than 20 nm and being in contact with the red light-emitting layer, the blue light-emitting layer being in contact with the green light-emitting layer, and the yellow light-emitting layer being in contact with the blue light-emitting layer.

25. The tandem white light-emitting OLED device of claim 20 wherein at least one of the white light-emitting units has the structure comprising: the yellow light-emitting layer being formed closest to the anode, the blue light-emitting layer being in contact with the yellow light-emitting layer, the green

light-emitting layer having a thickness greater than 0.5 nm and less than 20 nm and being in contact with the blue light-emitting layer, and the red light-emitting layer being in contact with the green light-emitting layer.

26. The tandem white light-emitting OLED device of claim 20 wherein at least one of the white light-emitting units has the structure comprising: the yellow light-emitting layer being formed closest to the anode, the green light-emitting layer having a thickness greater than 0.5 nm and less than 20 nm and being in contact with the yellow light-emitting layer, the blue light-emitting layer being in contact with the green light-emitting layer, and the red light-emitting layer being in contact with the blue light-emitting layer.

27. The tandem white light-emitting OLED device of claim 20 wherein at least one of the white light-emitting units has the structure comprising: the green light-emitting layer being formed closest to the anode, the blue light-emitting layer being in contact with the green light-emitting layer, the yellow light-emitting layer having a thickness greater than 0.5 nm and less than 5 nm and being in contact with the blue light-emitting layer, and the red light-emitting layer being in contact with the yellow light-emitting layer.

28. The tandem white light-emitting OLED device of claim 20 wherein at least one of the white light-emitting units has the structure comprising: the blue light-emitting layer being formed closest to the anode, the green light-emitting layer having a thickness greater than 0.5 nm and less than 20 nm and being in contact with the blue light-emitting layer, the yellow light-emitting layer having a thickness greater than 0.5 nm and less than 5 nm and being in contact with the green light-emitting layer, and the red light-emitting layer being in contact with the yellow light-emitting layer.

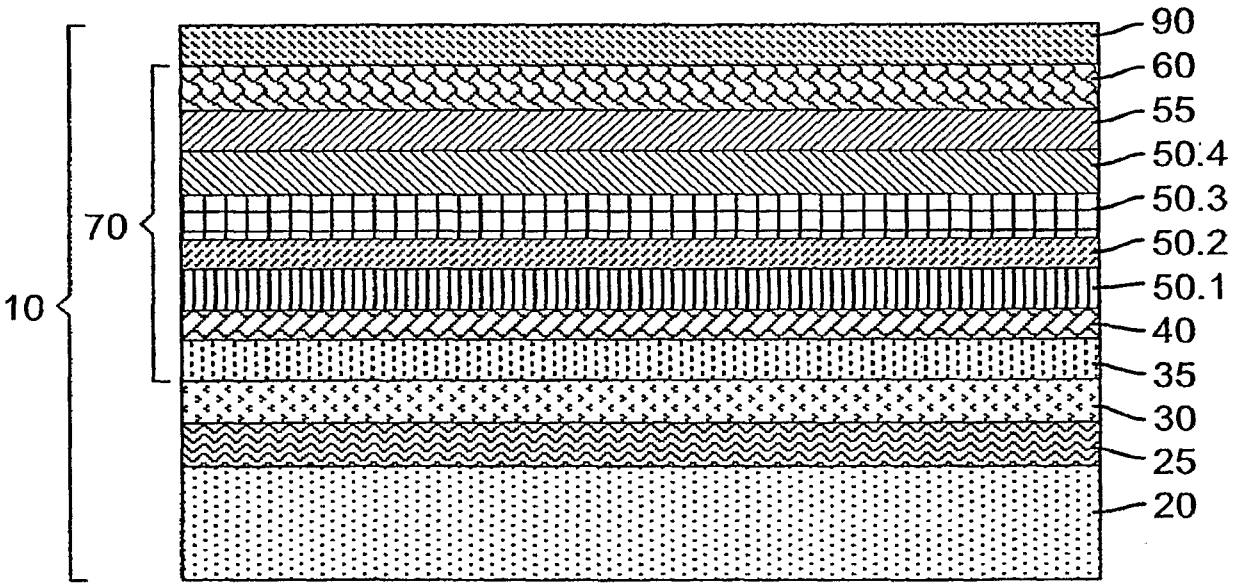


FIG. 1

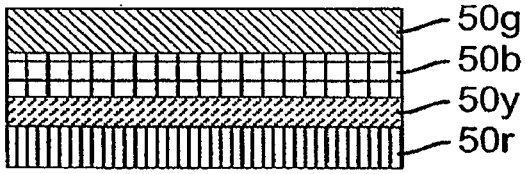


FIG. 2a

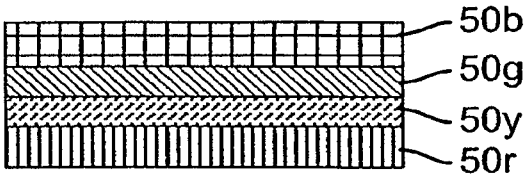


FIG. 2b

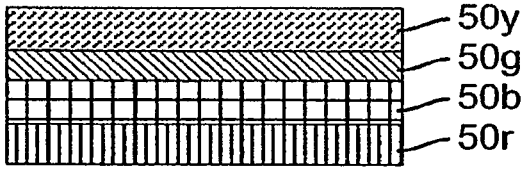


FIG. 2c

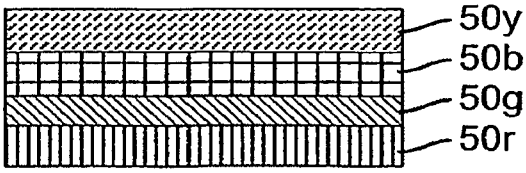


FIG. 2d

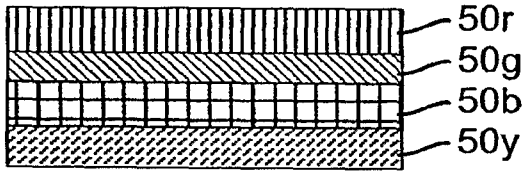


FIG. 2e

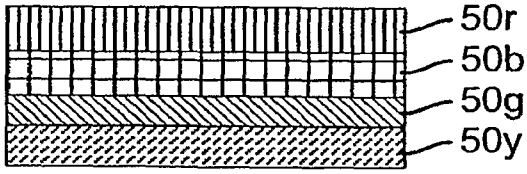


FIG. 2f

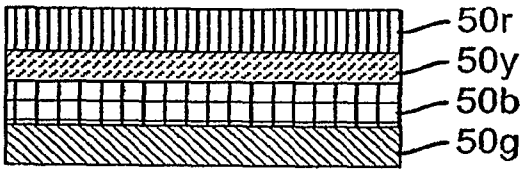


FIG. 2g

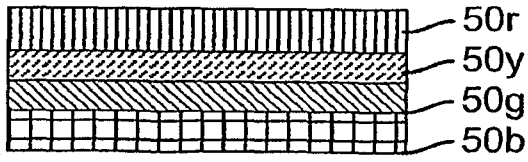
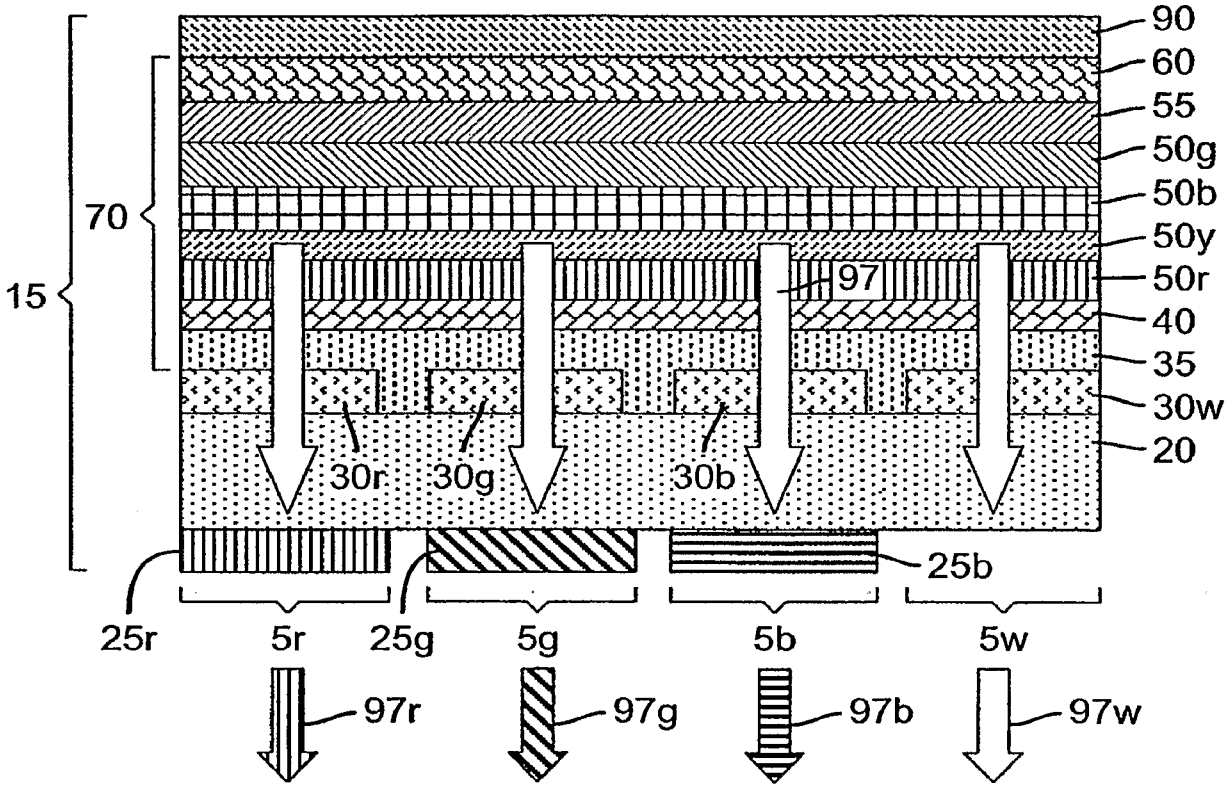


FIG. 2h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50g
50b
50y
50r
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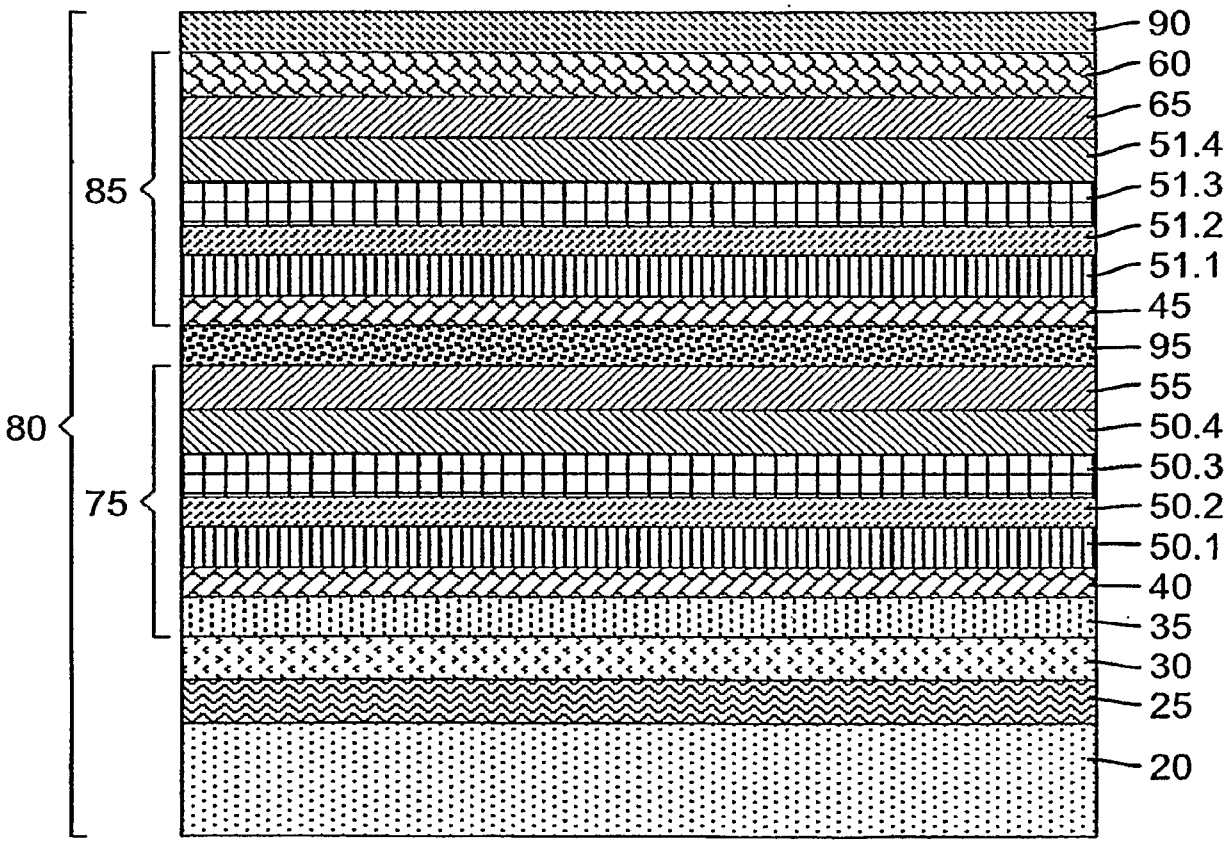
30w
20
70
15
97
30r
30g
30b
25b
25r
5r
25g
5g
5b
5w
97r
97g
97b
97w

FIG. 3


90
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51.4
51.3
51.2
51.1
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50.2
50.1
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35
30
25
20
85
75
80

FIG. 4

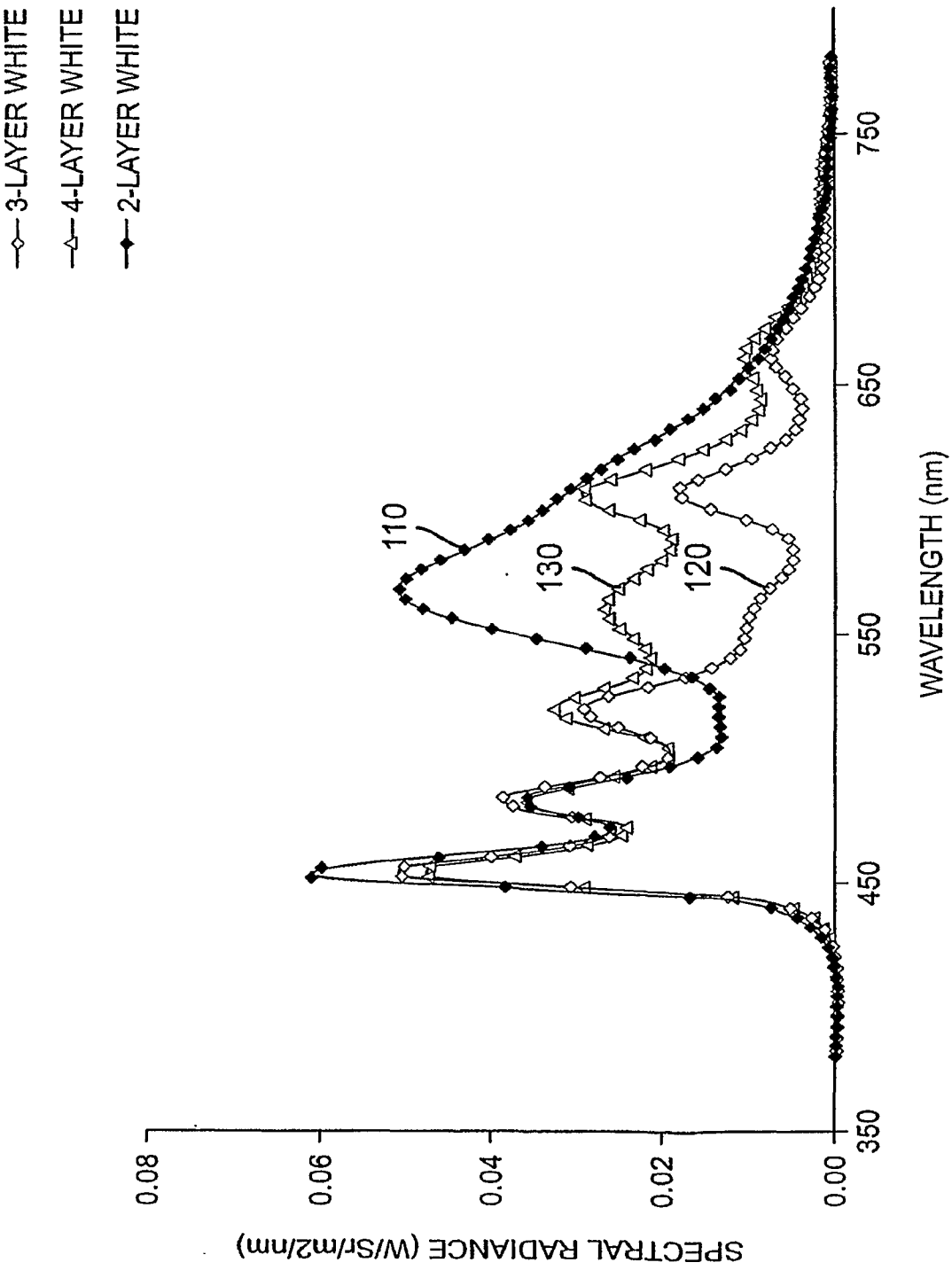
3-LAYER WHITE
4-LAYER WHITE
2-LAYER WHITE
110
130
120
SPECTRAL RADIANCE (W/Sr/m2/nm)
0.00
0.02
0.04
0.06
0.08
350
450
550
650
750
WAVELENGTH (nm)

FIG. 5

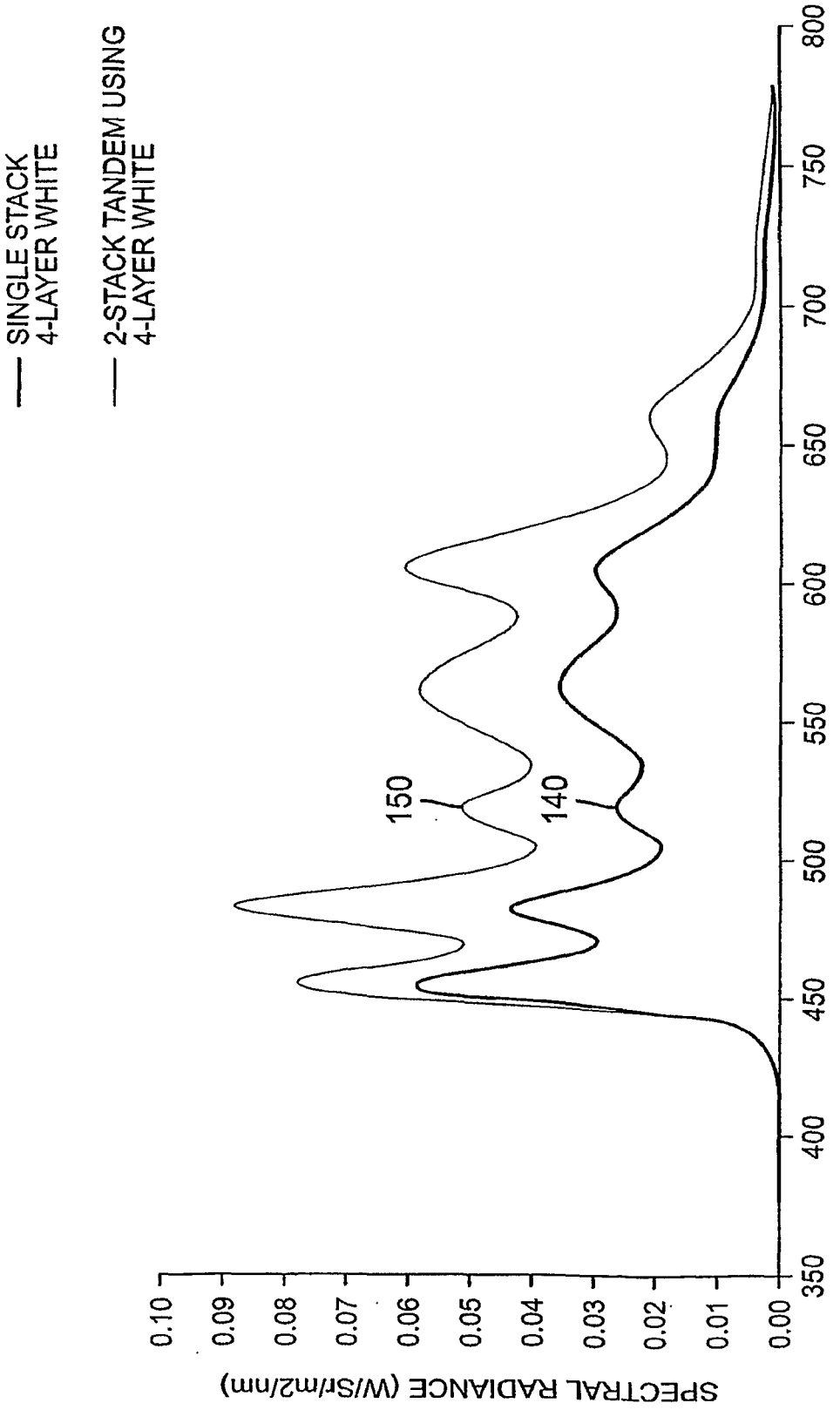
SINGLE STACK
4-LAYER WHITE
2-STACK TANDEM USING
4-LAYER WHITE
150
140
SPECTRAL RADIANCE (W/Sr/m2/nm)
WAVELENGTH (nm)
0.00
0.01
0.02
0.03
0.04
0.05
0.06
0.07
0.08
0.09
0.10
350
400
450
500
550
600
650
700
750
800

FIG. 6

INTERNATIONAL SEARCH REPORT

International application No
PCT/US2007/007452

A. CLASSIFICATION OF SUBJECT MATTER
INV. H01L51/50 H01L27/32

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

B. FIELDS SEARCHED

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

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 practical, search terms used)
EPO-Internal

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	JP 2006 040856 A (PENTAX CORP; ITC KK) 9 February 2006 (2006-02-09) abstract	1-28
Y	WO 2006/009024 A (KONICA MINOLTA HOLDINGS INC [JP]; SUZURI YOSHIYUKI [JP]; KITA HIROSHI) 26 January 2006 (2006-01-26) paragraphs [0019], [0027], [0042] - [0045], [0069] & EP 1 784 056 A (KONICA MINOLTA HOLDINGS INC [JP]) 9 May 2007 (2007-05-09)	1-28
Y	US 2006/040132 A1 (LIAO LIANG-SHENG [US] ET AL) 23 February 2006 (2006-02-23) paragraphs [0156] - [0169]	1-28

☐ Further documents are listed in the continuation of Box C.

☒ See patent family annex.

* Special categories of cited documents :

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

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

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

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

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

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

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

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

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
24 August 2007	31/08/2007

Name and mailing address of the ISA/	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL – 2280 HV Rijswijk Tel. (+31-70) 340-2040, Tx. 31 651 epo nl, Fax: (+31-70) 340-3016	Welter, Steve

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No
PCT/US2007/007452

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
JP 2006040856 A	09-02-2006	NONE	
WO 2006009024 A	26-01-2006	EP 1784056 A1	09-05-2007
EP 1784056 A	09-05-2007	WO 2006009024 A1	26-01-2006
US 2006040132 A1	23-02-2006	EP 1787316 A1	23-05-2007
		KR 20070043014 A	24-04-2007
		WO 2006023322 A1	02-03-2006

专利名称(译)	带滤光片的高效白光OLED显示屏		
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申请号	EP2007754029	申请日	2007-03-19
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摘要(译)

一种白色发光OLED器件，包括：阳极和阴极;在阳极和阴极之间提供至少四个发光层，其中当电流在阳极和阴极之间通过时，四个发光层中的每一个产生不同的发射光谱，并且这种光谱组合形成白光;其中所述四个发光层包括红色发光层，黄色发光层，蓝色发光层和绿色发光层，其布置为：i）每个发光层层与至少一个其他发光层接触，ii）蓝色发光层与绿色发光层接触，和iii）红色发光层仅与另一个光接触 - 发光层。