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Bulovic et al.

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[54] **HIGH EFFICIENCY ORGANIC LIGHT EMITTING DEVICES WITH LIGHT DIRECTING STRUCTURES**

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[73] Assignee: **The Trustees of Princeton University**, Princeton, N.J.

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[22] Filed: **Dec. 23, 1996**

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[51] Int. Cl.⁶ **H01J 1/62**; B32B 7/00; H05B 33/14

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[52] U.S. Cl. **313/506**; 428/917

[58] Field of Search 313/504, 506, 313/509, 512, 503, 498, 501; 428/917, 690; 315/169.3, 382.1; 434/307 R; 362/24, 88, 812; 345/30

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Primary Examiner—Jay M. Patidar
Attorney, Agent, or Firm—Kenyon & Kenyon

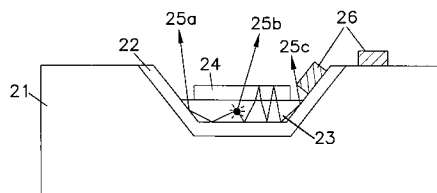
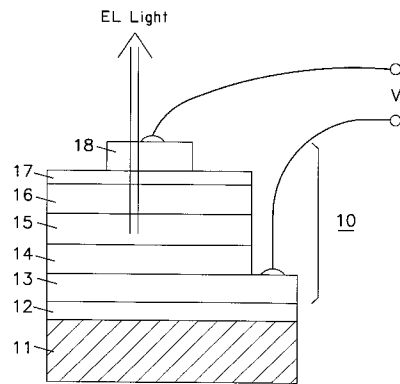
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[57] ABSTRACT

An organic light emitting device (OLED) structure having reflective surfaces is fabricated in a pit formed in a substrate. The pit has slanted reflective side walls which redirect light that is waveguided in the organic layers of the OLED to a direction substantially normal to the plane of the substrate. The reflective structure can also be formed with a planar configuration over interconnects covered with a polyimide.

31 Claims, 9 Drawing Sheets



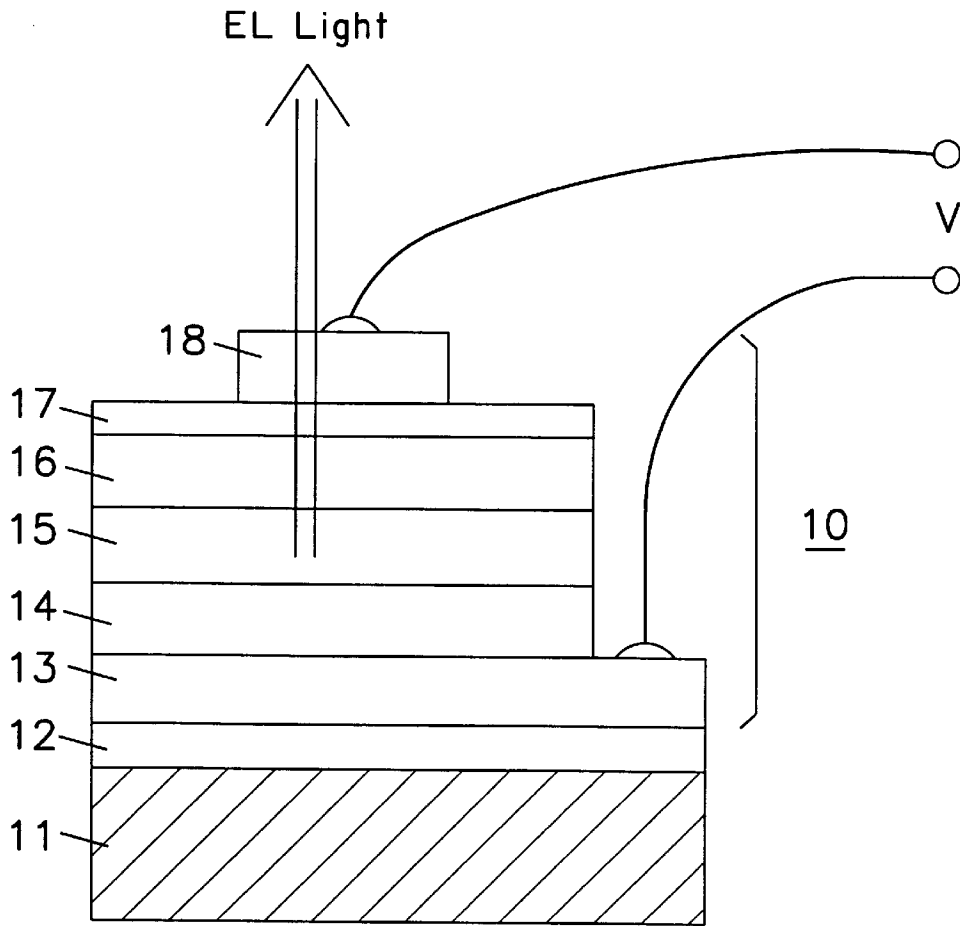


FIG. 1

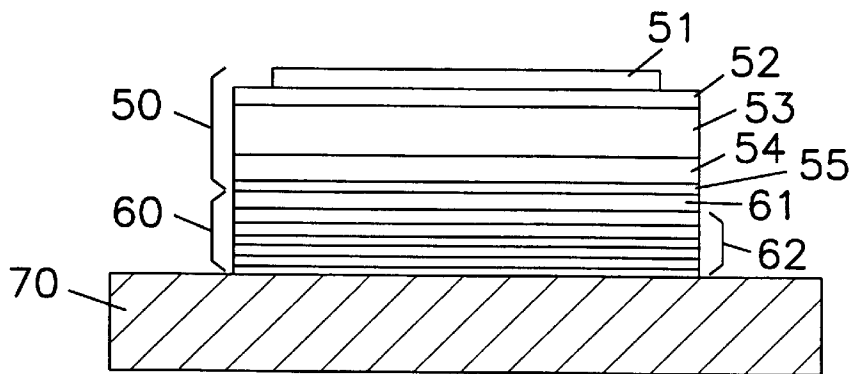


FIG. 5

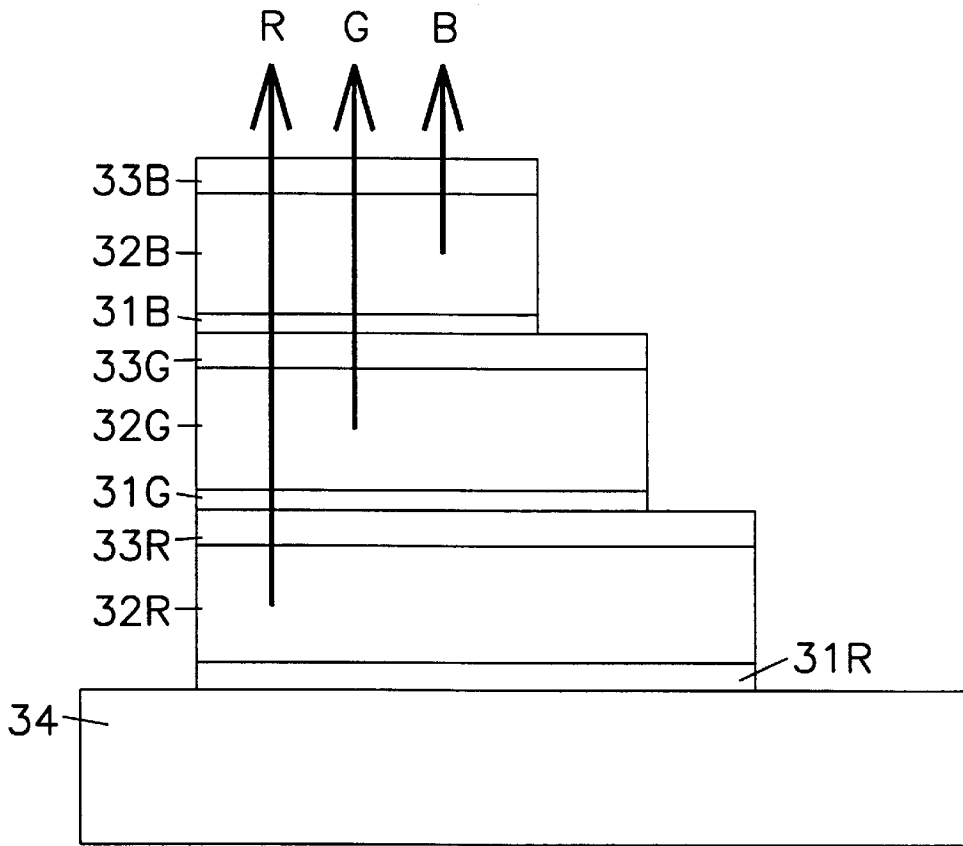


FIG.2

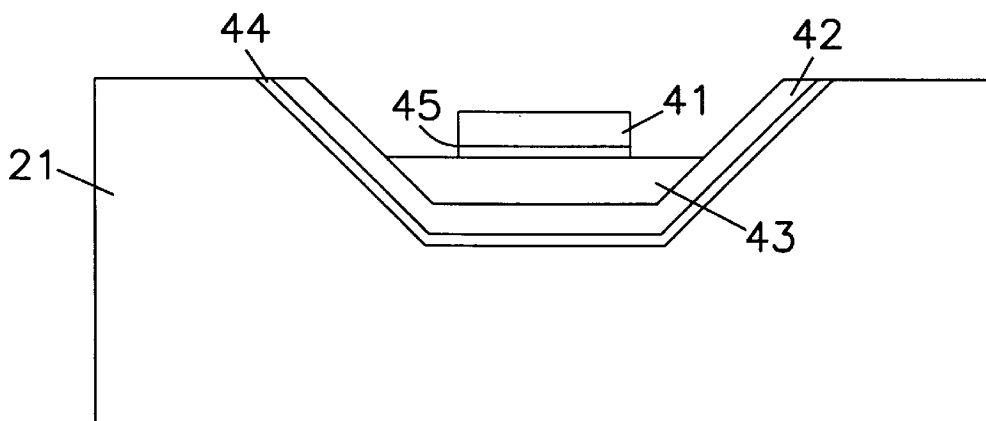


FIG.3C

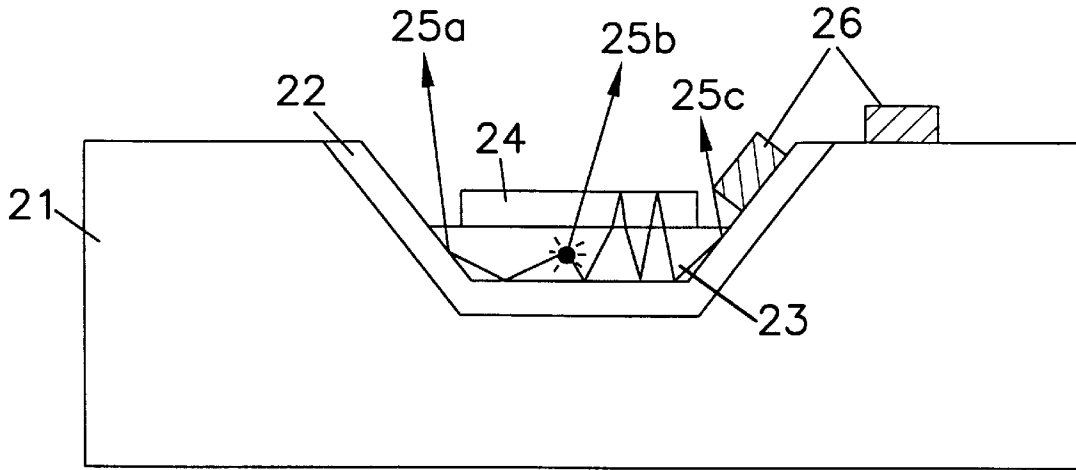


FIG.3A

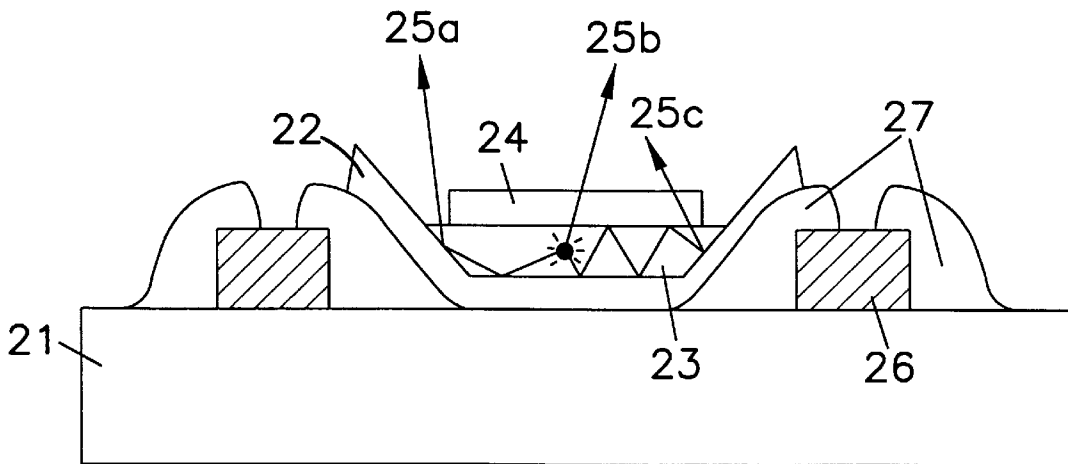


FIG.3B

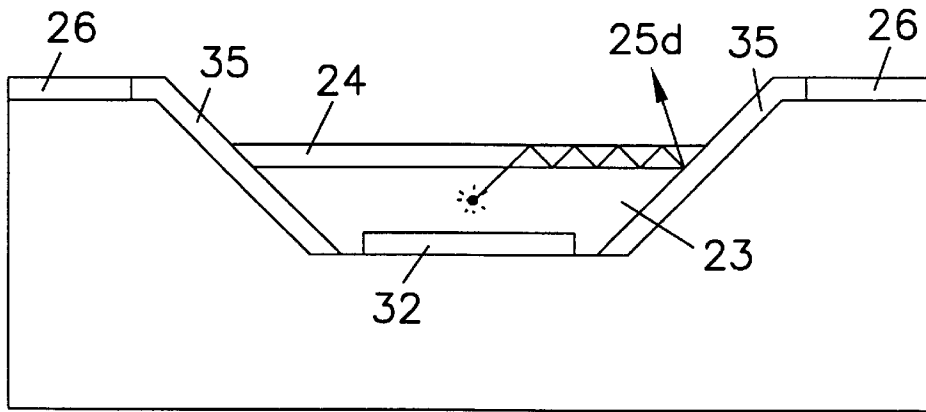


FIG.3D

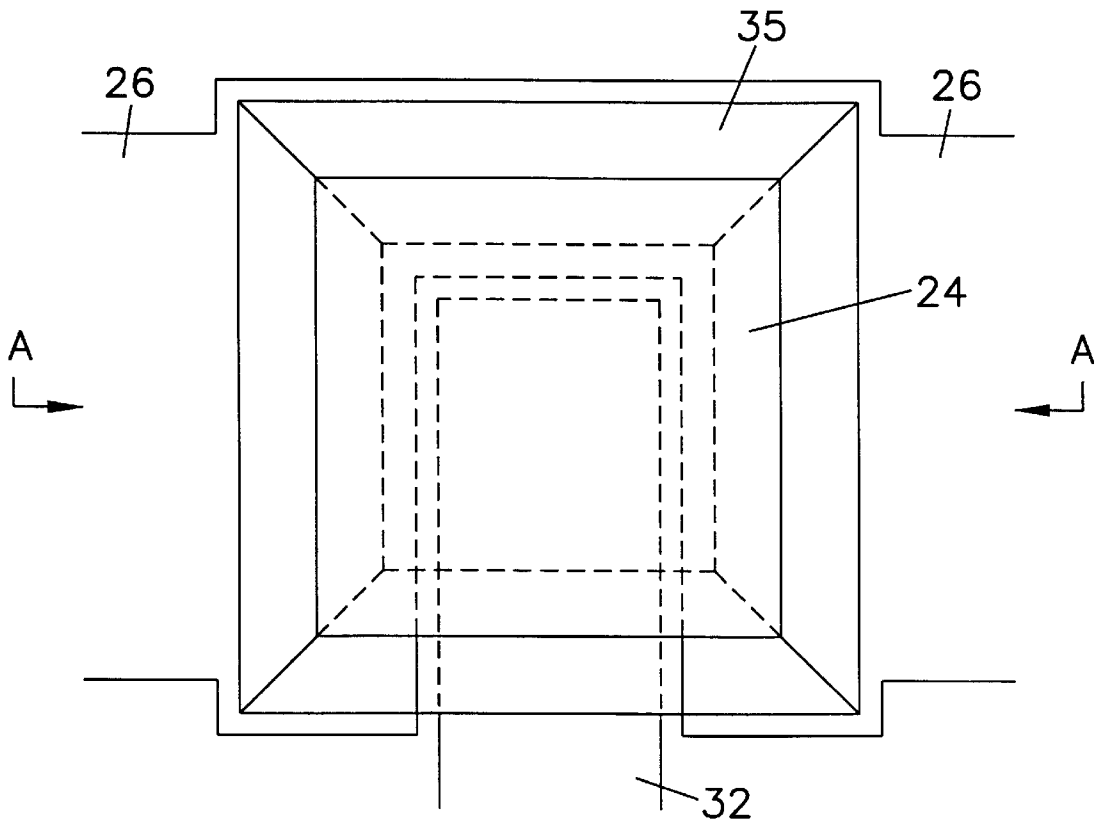


FIG.3E

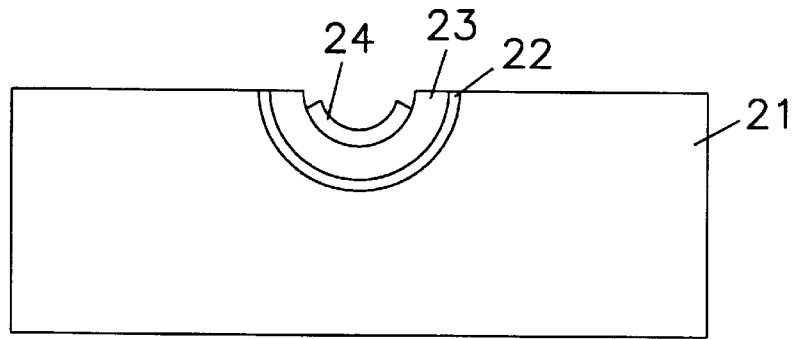


FIG. 3F

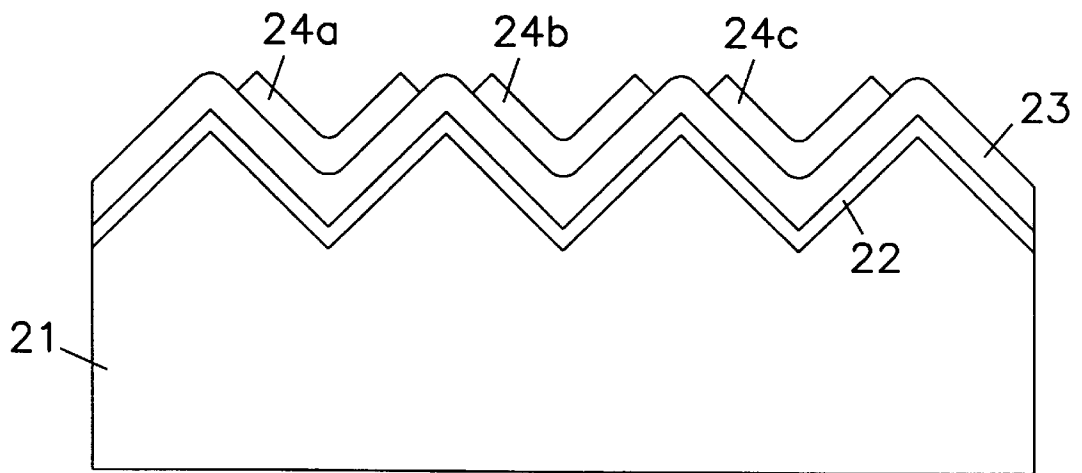


FIG. 3G

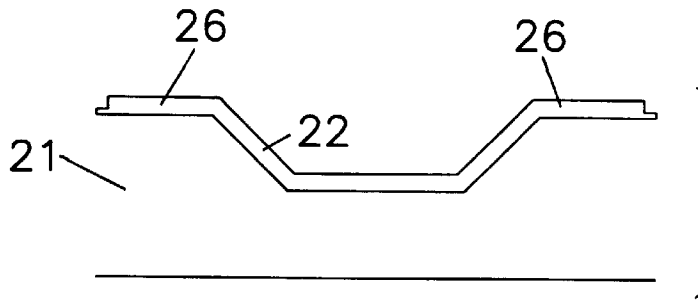


FIG. 4A

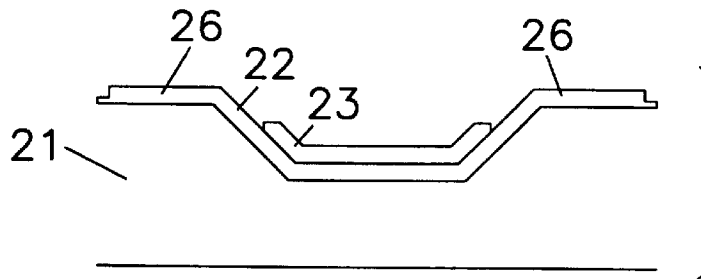


FIG. 4B

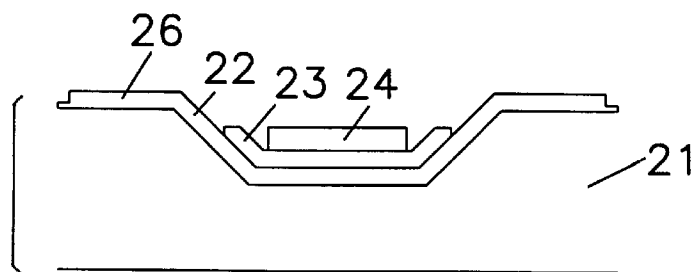


FIG. 4C

FIG. 4X

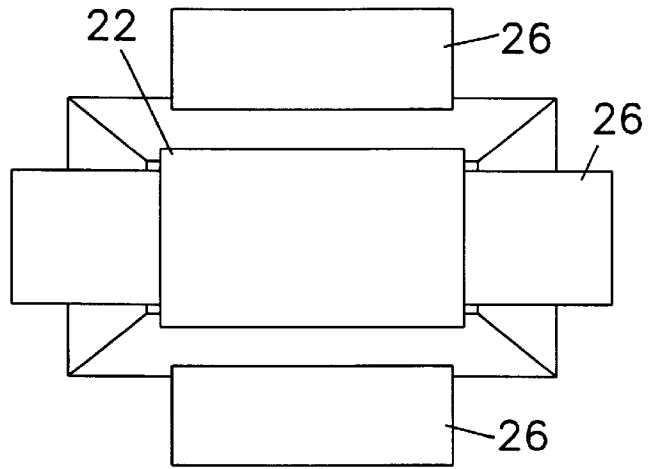


FIG. 4Y

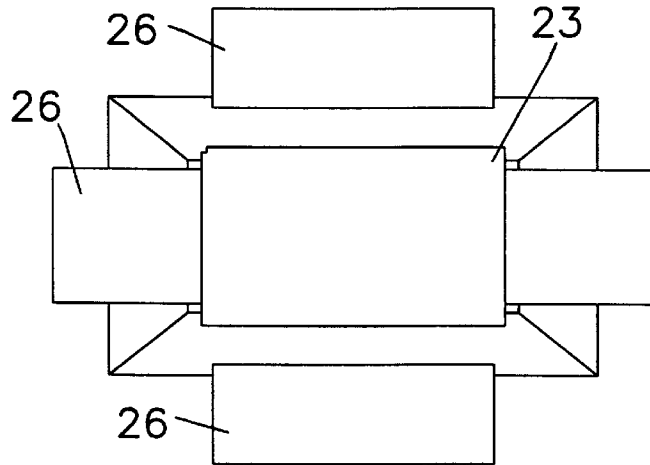
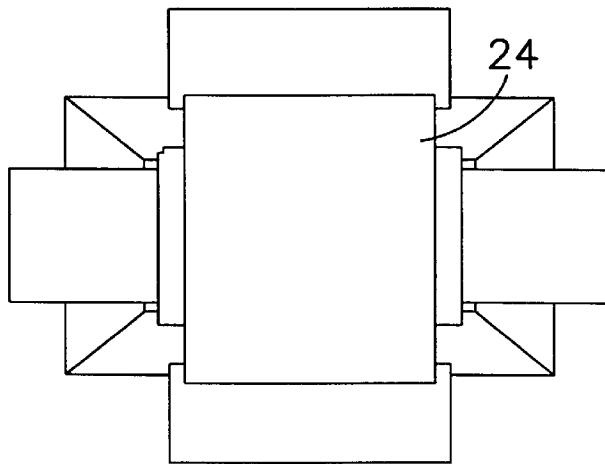


FIG. 4Z



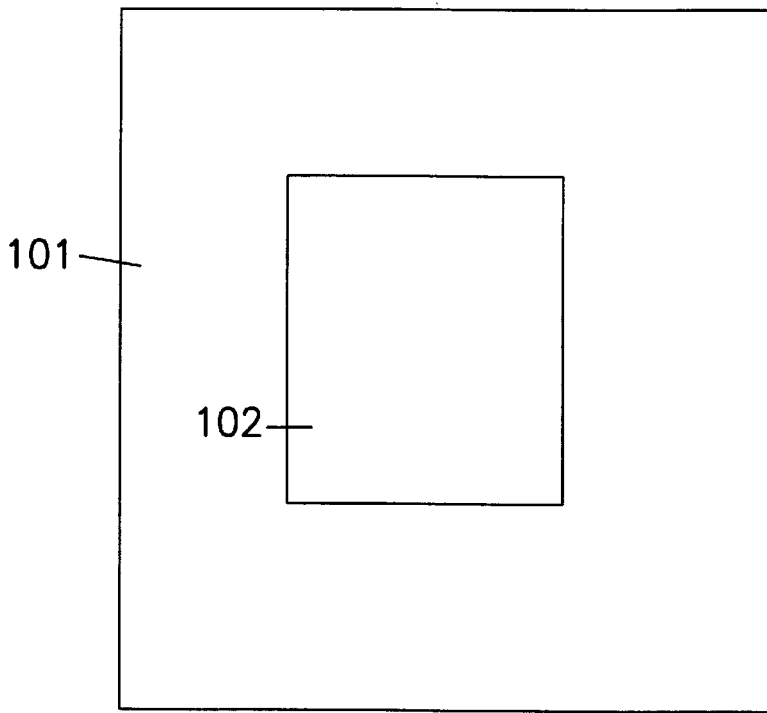


FIG. 6

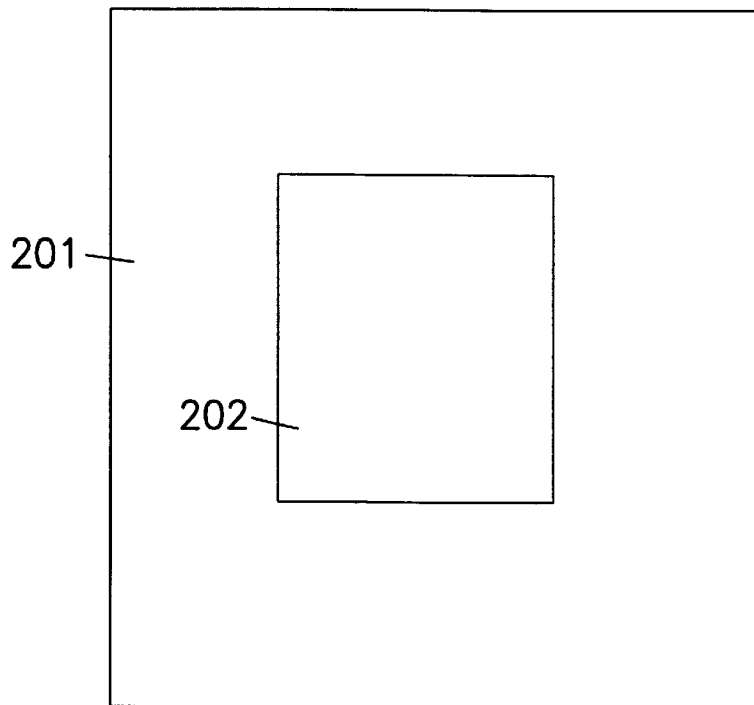


FIG. 7

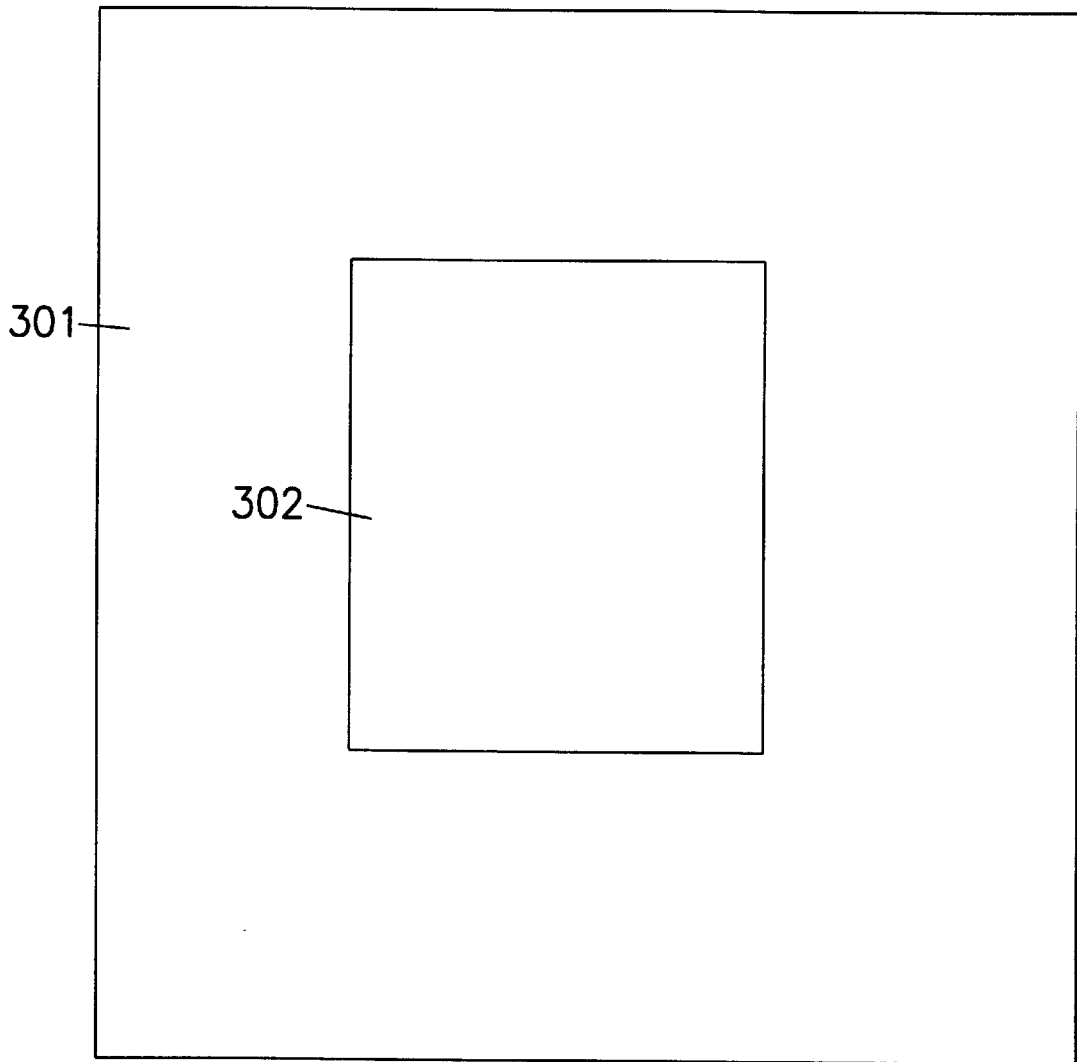


FIG. 8

HIGH EFFICIENCY ORGANIC LIGHT EMITTING DEVICES WITH LIGHT DIRECTING STRUCTURES

FIELD OF THE INVENTION

The present invention relates to the field of light emitting devices, in particular, to organic light emitting devices (OLEDs) and to methods of producing same.

BACKGROUND OF THE INVENTION

OLEDs are light emitting devices which use organic electroluminescent (EL) materials excited by electric current to emit light. A conventional OLED structure is described in an article by C. W. Tang and S. A. VanSlyke, "Organic Electroluminescent Diode", *Applied Physics Letters*, Vol. 51, 913 (1987) ("Tang & VanSlyke 1987"). Tang and VanSlyke describe a device in which an indium tin oxide (ITO) anode is placed on a glass substrate and covered successively with a hole transport layer composed of an aromatic diamine, a luminescent layer composed of tris-(8-hydroxyquinoline) aluminum (Alq₃) and a metallic cathode composed of a magnesium/silver (Mg:Ag) alloy. EL light is emitted by the recombination of holes and electrons in the luminescent Alq₃ layer. In this structure, the EL light is emitted down through the hole transport and ITO layers and the glass substrate.

Conventional OLEDs, however, suffer from several drawbacks and limitations.

In order to use OLEDs in a display application, it is necessary to integrate the OLEDs with circuitry, such as active matrix display drivers, which will power and control the OLEDs. Such control and power circuitry can be based on different technologies, some of which deliver positive and others negative voltage to the OLED. For technology which delivers negative voltage to the OLED (such as amorphous Si NFETs), it is necessary to have the OLED cathode in contact with the circuit's driving element. The bottom terminal of a conventional OLED, however, is an anode. This limits the ability to integrate negative voltage technology control circuitry with conventional OLEDs.

Conventional OLEDs also have long-term reliability problems. Degradation mechanisms of OLED have been extensively investigated recently. It is commonly understood that the exposure of a conventional OLED to air while the device is in operation accelerates device degradation, as described in P. E. Burrows et al. "Reliability and Degradation of Organic Light Emitting Devices", *Applied Physics Letters*, Vol. 65, 2922 (1994). More specifically, degradation mechanisms involving the top metal electrode of conventional OLEDs have been observed.

Another problem experienced with conventional OLEDs is that a significant portion of the EL light generated in the OLED is not emitted in a direction normal to the device, but is rather waveguided in the substrate, which must be substantially transparent, or in the organic films. This problem is described in D. Z. Garbuzov et al., "Photoluminescence Efficiency and Absorption of Aluminum-tris-quinolate (Alq₃) Thin Films", *Chemical Physics Letters*, Vol. 249, 433 (1996). The waveguided light does not reach the observer standing in front of the OLED and is effectively lost, thereby reducing the effective efficiency of the OLED.

SUMMARY OF THE INVENTION

The present invention is directed to high reliability, high efficiency, integratable OLED structures which overcome many of the disadvantage of conventional OLEDs.

In contrast to known OLEDs, the OLED of the present invention has an inverted structure (and as such will be alternatively referred to as an "inverted OLED" or IOLED) which provides the OLED of the present invention with several advantages over known OLED structures.

IOLEDs can be grown on any sufficiently flat substrate to which a magnesium/silver (Mg:Ag) alloy will adhere. The substrate can be opaque or transparent, flexible or rigid. Since light is emitted from the top side of the IOLED, the device can be grown on top of opaque substrates, in contrast to a conventional OLED which must be grown on a transparent substrate. IOLEDs can therefore be deposited directly on top of integrated circuits (such as a silicon-based array of transistors) which could provide power to and control OLED operation in a display application. For control circuit technology which delivers negative voltage to the OLED (such as amorphous silicon NFETs), it is necessary to have the OLED cathode in electrical contact with the circuit's driving element. Unlike a conventional OLED, the bottom terminal of the IOLED is a cathode which makes it possible to deposit the IOLED directly onto such a driving circuit.

Furthermore, because an IOLED in accordance with the present invention can be grown on any sufficiently flat substrate, the substrate can be thin. Such an inverted OLED on a thin substrate can be used in xerographic printing, thereby eliminating the need for lensing in printer bars.

The IOLED of the present invention also provides improved reliability over conventional OLEDs. In the IOLED of the present invention, the metal electrode is on the bottom of the device, protected from exposure to atmosphere by the overlying organic layers as well as by an ITO (Indium Tin Oxide) electrode arranged on the top of the IOLED. Because the ITO material is an oxide, the ITO electrode is not susceptible to appreciable atmospheric degradation.

Furthermore, the IOLED can be grown on top of atomically smooth substrates. This avoids device degradation due to roughness imperfections of ITO or embedded particles. In contrast, conventional OLEDs are grown on ITO coated substrates which invariably exhibit some roughness.

IOLEDs can also be stacked, with a second OLED grown on top of the first. Conventional transparent OLEDs can also be stacked on top of IOLEDs and vice versa, thereby increasing overall design flexibility.

The present invention also provides an OLED structure for improving emission efficiency. In accordance with the present invention, EL light that would otherwise be waveguided in the substrate or organic films of an OLED, and thus not emitted normal to the device toward the observer, can be redirected towards the observer by reflective side walls built into a patterned substrate on which the OLED is grown, thereby increasing the effective efficiency of the OLED. Such a structure in accordance with the present invention comprises a substrate, a first electrode formed on a top surface of the substrate, a first organic layer formed on the first electrode, a second organic layer formed on the first organic layer, and a second electrode formed on the second organic layer, wherein the first electrode is applied over a pit formed into the top surface of the substrate, the first electrode being reflective so as to redirect light in a direction substantially perpendicular to the top surface of the substrate, and wherein at least one of the first and second organic layers emits a light upon application of a voltage between the first and second electrodes.

The OLED of the present invention can be used in a wide variety of applications, including computer displays, infor-

mational displays in vehicles, television monitors, telephones, printers, illuminated signs, large-area screens and billboards.

DRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 shows an OLED structure in accordance with the present invention.

FIG. 2 shows a stacked OLED structure in accordance with the present invention.

FIGS. 3A through 3G show structures for improving the efficiency of OLEDs in accordance with the present invention.

FIGS. 4A through 4C and 4X through 4Z are cross-section and plan views respectively, of an OLED structure with interconnects undergoing successive fabrication steps.

FIG. 5 shows an OLED in accordance with the present invention including a distributed Bragg reflector structure.

FIG. 6 shows a display including a plurality of light emitting devices.

FIG. 7 shows a vehicle, television or computer incorporating a display incorporating a light emitting device.

FIG. 8 shows a printer, screen, sign telecommunications device or telephone incorporating a light emitting device.

DETAILED DESCRIPTION

FIG. 1 shows the device structure of an inverted organic light emitting device (IOLED) **10** in accordance with the present invention. The IOLED **10** is grown on a substrate **11**, which can be either opaque or transparent, flexible or rigid. As such, the substrate can be composed of a wide variety of materials, such as polystyrene or aluminum foil. Any roughness present on the surface of the substrate **11** can be smoothed by depositing an optional thin layer of polymer **12** on top of the substrate, or by applying a similar smoothing technique. The IOLED **10** is deposited on top of the smoothed substrate.

The IOLED structure comprises a cathode **13** on top of which an electron transporting layer (ETL) **14**, an electroluminescent (EL) layer **15**, a hole transporting layer (HTL) **16**, a protection layer **17**, and an anode **18** are deposited in sequence.

The cathode **13** injects electrons into the ETL **14**, while the anode **18** injects holes into the protection layer **17** which in turn injects the holes into the HTL **16**. The ETL and HTL conduct electrons and holes, respectively, into the EL layer, where the two kinds of carriers recombine, generating EL light.

In a further embodiment of the IOLED of the present invention, a single organic layer can perform the functions of both the ETL **14** and EL layer **15**. In the alternative, a single organic layer can act as both the HTL **16** and EL layer **15**.

The protection layer **17** protects the underlying soft organic layers against damage caused by the deposition of the ITO anode **18**. The protection layer **17** should have a sufficiently high hole conductivity to allow sufficient injection of holes into the HTL **16** for the device to operate.

The protection layer **17** can be formed by the deposition of 3,4,9,10-perylenetetracarboxylic dianhydride (PTCDA), bis(1,2,5-thiadiazolo)-p-quinobis(1,3-dithiole) (BTQBT), copper phthalocyanine (CuPc), or other suitable, more rigid organic materials. The protection layer **17** does not significantly contribute to absorption of the emitted EL light, as it is very thin (approx. 50–500 Å) and possibly transparent to EL emissions. Also, only a small fraction of the total voltage

is dropped through the protection layer **17** because it is conductive and very thin compared to the rest of the device.

Moreover, with the IOLED structure of the present invention, the ETL **14** is not damaged by the deposition of the metallic cathode **13** because the ETL is deposited on top of the cathode. This is in contrast to a conventional OLED structure in which the cathode is deposited on the ETL.

In an exemplary embodiment of the IOLED of the present invention, the substrate **11** was formed from polished (100) Si. Prior to deposition of the IOLED, the substrate was cleaned by sequential ultrasonic rinses in detergent solution and deionized water, followed by a boil in 1,1,1-trichloroethane, a rinse in acetone and a boil in 2-propanol. Between each cleaning step, the substrate was dried in pure nitrogen gas. In this embodiment, the smoothing layer **12** was omitted as the surface of the polished (100) Si was sufficiently smooth. The cathode **13** was formed as a 2000 Å layer of Mg:Ag alloy (in a mass ratio of 5:1). The cathode **13** can typically be 500 to 2000 Å thick. The ETL **14** and the EL layer **15** were formed as one 650 Å layer of Alq₃ and the HTL **16** was formed as a 300 Å layer of N,N'-diphenyl-N,N'-bis (3-methylphenyl)-1-1'-biphenyl-4,4'-diamine (TPD) or 4,4'-bis[N-(1-naphthyl)-N-phenyl-amino]biphenyl (α -NPD). The protection layer **17** was formed as a 120 Å layer of PTCDA, and the anode **16** was formed with a 950 Å layer of ITO. The protection layer can typically be 20 to 170 Å thick.

The Mg:Ag, Alq₃, TPD, and PTCDA layers were deposited by thermal evaporation from resistively heated molybdenum boats at an ambient pressure of 1×10^{-6} Torr. (The pressure rose to 1×10^{-5} Torr during Mg:Ag deposition.) The typical deposition rate ranged from 1 to 5 Å/second. The ITO layer was deposited by RF sputtering of a pressed ITO target in the ambient atmosphere composed of argon and oxygen (in a volume ratio of 2000:1), and 5 mTorr pressure. The RF power was 5 W, which resulted in a deposition rate of 200 Å/hour.

Instead of Alq₃, the EL layer can also be formed using emissive compounds disclosed in co-pending U.S. patent application Ser. No. 08/771,815, titled NOVEL MATERIALS FOR MULTICOLOR LED's, and U.S. patent application Ser. No. 08/774,087, titled RED OLED's, filed on even date herewith and incorporated herein by reference in their entirety. The emissive compounds disclosed therein can be selected to emit light of a desired range of wavelengths.

The ETL can also be formed using a compound such as that disclosed in co-pending U.S. patent application Ser. No. 08/774,120, titled ELECTRON TRANSPORTING AND LIGHT EMITTING LAYERS BASED ON ORGANIC FREE RADICALS, filed on even date herewith and incorporated herein by reference in its entirety. The compound disclosed therein is comprised of a stable chemical radical.

OLEDs fabricated in accordance with the present invention have been demonstrated to have a superior lifetime in air compared to conventional OLEDs (e.g., such as that described in Tang and VanSlyke 1987).

IOLEDs in accordance with the present invention can also be stacked, with multiple OLEDs grown on top of each other. FIG. 2 shows a structure with three stacked IOLEDs that emit red, green and blue light, respectively, to form a true color pixel. Each of the three OLEDs can be independently controlled. Layers **31R**, **31G** and **31B** are cathode layers and **33R**, **33G** and **33B** are the anode layers for the red, green and blue IOLEDs, respectively. The ETL, EL layer, HTL and protection layer are illustrated as single blocks **32R**, **32G** and **32B** for the red, green, and blue

IOLEDs, respectively. Note that cathode layers **31G** and **31B** should be very thin (less than 200 Å) in order to be transparent. The stacked structure is grown on top of a substrate **34**.

In the stacked structure of FIG. 2, the anodes **33R**, **33G** and **33B** of the OLEDs in the stack are each deposited on top of a protection layer. The three protection layers are of identical composition. In order to emit the three different colors, however, the three organic ETL/EL layers beneath the protection layers are of different composition. In a conventional stacked OLED structure which does not include protection layers, a cathode would be deposited over each ETL/EL layer directly, with each ETL/EL layer being different from the other ETL/EL layers. In the stacked structure of the present invention, however, an anode is deposited over each protection layer, each protection layer being the same as the other protection layers. This allows for a greater chance of growing a working structure, thereby improving manufacturing yields.

A conventional transparent OLED can be stacked on top of an IOLED and vice versa, thereby increasing overall design flexibility.

The present invention also provides an OLED structure with superior efficiency, compared to conventional structures, in coupling EL light out of the OLED. With conventional OLEDs, a significant fraction of the EL light generated in the OLED is not emitted in the direction normal to the device, but is rather waveguided in the substrate or the organic films. The waveguided light does not reach the observer standing in front of the OLED and is effectively lost. In accordance with the present invention, an OLED is grown on a patterned substrate that is structured to redirect the waveguided light towards the observer, thereby increasing the effective efficiency of the OLED. This structure can also be adapted for use with conventional OLEDs.

FIG. 3A shows a device structure utilizing an IOLED fabricated on a patterned substrate **21** which redirects waveguided light **25c** in a direction substantially normal to the substrate. The IOLED comprises a cathode **22**, organic layers **23** (shown for simplicity as one layer) and an anode **24**. In the exemplary structure of FIG. 3A, the IOLED is grown in a patterned substrate having a pit with a flat bottom surface and 45° slanted side walls (i.e., each side wall forms an angle of substantially 135° with the bottom surface of the pit). The OLED cathode **22** is first deposited over the pit area, including the slanted walls. The OLED cathode, which is metallic, also acts as a mirror to reflect light emitted by the OLED. After deposition of the cathode, the organic layers **23** and the ITO anode **24** are then deposited.

Light generated in the organic layers can be either transmitted through the top anode **24**, e.g. light ray **25b**, reflected from one of the mirrored walls, e.g. light ray **25a**, or waveguided in the organic layers **23** and/or the top ITO electrode **24** and then reflected from one of the mirrored walls, e.g. light ray **25c**.

The depth of the pit in which the reflective OLED structure is formed can be relatively shallow, on the order of 1000–3000 Å, and as wide as desired.

Interconnects **26** for connecting the OLED to control circuitry or to other OLEDs, as in a matrix arrangement, are shown in FIG. 3A. One of the interconnects **26** is coupled to the anode and the other interconnect is coupled to the cathode of the OLED shown.

A reflective structure similar to that of FIG. 3A can also be formed in a planarized structure as shown in FIG. 3B. In this structure, the OLED cathode **22** is deposited over a

polyimide layer **27** that partially covers the interconnects **26**. The cathode **22** conforms to the shape of the polyimide **27** which is readily shapable or moldable so as to impart to the cathode the desired slope and shape.

An advantage of the OLED structure of the present invention is that it can be built compactly and is independent of substrate transparency or composition. As such, the OLED of the present invention can also be grown on a reflective metal foil.

If the structure is grown in a pitted substrate (as in FIG. 3A) the interconnect lines **26** can be placed on the side walls and on the substrate. If the structure is grown over a planar substrate (as in FIG. 3B) the interconnect lines can be placed on the substrate.

The arrangements of FIGS. 3A and 3B can also be adapted to non-inverted OLEDs. FIG. 3C shows a structure similar to that of FIG. 3A adapted for use with a substantially transparent OLED (TOLED). TOLEDs are described in U.S. patent application Ser. No. 08/613,207 which issued as U.S. Pat. No. 5,703,436 incorporated herein by reference in its entirety. As described above, the substrate **21** is provided with a pit having 45-degree slanted walls. A metallic layer **44** is first deposited over the pit area, including the slanted walls. The metallic layer **44** is typically composed of aluminum (Al) or gold (Au) and serves as a reflective surface. An anode layer **42** composed of ITO is then deposited over the metallic layer **44** and organic layers **43** are then deposited over the ITO anode **42**. A thin (e.g. less than 100 Å thick), substantially transparent metallic layer **45** composed of an Mg:Ag layer is then deposited on the organic layer **43** and is then covered with a cathode **41** composed of ITO.

FIGS. 3D and 3E are cross-section and plan views, respectively, of a further embodiment of the present invention. (FIG. 3D shows the section A—A indicated in FIG. 3E.) Some of the light emitted in the organic layers **23** is also trapped by waveguiding in the ITO anode layer **24**. This is illustrated in FIG. 3D by the light ray **25d**. To redirect the light that is waveguided in the ITO layer **24**, it is desirable to extend the ITO layer **24** to the reflective, slanted side walls, as shown in FIG. 3D. As described above, the side walls are made reflective by the deposition of a metallic layer, in this case, layer **35**. Because in this embodiment the ITO anode **24** is in contact with the metallic layer **35**, the metallic cathode **32** must be electrically isolated from the metallic layer **35**, as shown in FIGS. 3D and 3E.

In the embodiment of FIGS. 3D and 3E, a metallic layer is deposited over the entire pit area and then etched into two regions, thereby forming the cathode **32** and the reflective metallic layer **35**. The organic layers **23** are then deposited into the pit and covered with a layer of ITO which forms the anode **24**. The anode **24** is in electrical contact with the metallic layer **35**. As such, the metallic layer **35** can be integral with the interconnects **26**. As shown in FIG. 3E, the layer **35** provides a direct metallic path from one side of the OLED to the other, thus allowing multiple, similarly fabricated OLEDs to be interconnected in a row and thereby facilitating the interconnection of multiple OLEDs in a regular arrangement, such as in a matrix.

In addition to the pit structures shown so far, which have straight, slanted reflective side walls, other cross-sections are also possible. FIG. 3F shows another exemplary embodiment in which a pit with a semicircular cross-section, e.g., a hemispherical pit, is used.

In yet a further exemplary embodiment, a reflective structure can be fabricated over a substrate **21** with a sawtooth patterned top surface, as shown in FIG. 3G. In the

exemplary embodiment of FIG. 3G, three IOLEDs are formed with an individual ITO anode **24a**, **24b**, **24c** for each IOLED and a common cathode **22** and common organic layers **23**.

An arrangement for interconnecting the inverted reflective OLED structure of FIG. 3A will now be described with reference to FIGS. 4A through 4C and 4X through 4Z. This arrangement is well suited, for example, for interconnecting a plurality of OLEDs in a matrix in which each OLED is coupled to a row and a column of interconnects **26**.

FIGS. 4A through 4C are cross-sectional views of an OLED undergoing successive processing steps, and FIGS. 4X through 4Z are corresponding plan views.

As shown in FIGS. 4A and 4X, the metallic cathode **22** and interconnects **26** are deposited first onto the pit-structured substrate **21**. The cathode **22** is in contact with a row-oriented interconnect **26**. The organic layer **23** is then deposited over the cathode **22**, as shown in FIGS. 4B and 4Y. The organic layer **23** includes the protection layer, ETL, EL layer and HTL. The ITO anode **24** is then deposited over the organic layer **23** as shown in FIGS. 4C and 4Z. As shown in FIG. 4Z, the ITO anode **24** is coupled to the interconnect segments **26** which are arranged in a column and also acts as a bridge between the two interconnect segments.

In order to extract even more EL light in the direction normal to the OLED, an antireflection (AR) coating can be deposited on the transparent ITO anode. For a conventional OLED, this entails depositing the AR coating on top of the transparent substrate prior to the deposition of the ITO layer and the rest of the OLED layers. In such a configuration, care must be taken to account for the reflections in the transparent substrate. For an IOLED, the EL light does not travel through the substrate, simplifying the AR coating design. Also, with the IOLED, the AR coating can be deposited directly on the anode and thus can at the same time serve as a passivating layer for protecting the IOLED from atmosphere-related degradation.

Furthermore, in the IOLED structure of the present invention, the organic layers are deposited on top of the metallic cathode layer, as opposed to conventional OLEDs in which the cathode is deposited on the organic layer. As such, the organic layers of the IOLED are not damaged, as are the organic layers of a conventional OLED, by the deposition of the cathode layer. As a result, materials such as Alq₃ in the organic layers of the IOLED of the present invention can be expected to exhibit a better EL quantum efficiency than in a conventional OLED structure.

The IOLED structure of the present invention can also be fabricated with one or more filter structures for controlling the spectral width of the light emitted. FIG. 5 shows an IOLED **50** fabricated over a distributed Bragg reflector (DBR) structure **60** which is fabricated on a substrate **70**. The DBR structure **60** is formed as a ¼-wavelength stack **62** of highly reflective layers of dielectric material. The stack **62** can be formed with two to ten alternating layers of titanium oxide TiO₂ and silicon oxide SiO₂. A layer **61** of ITO is deposited on the stack **62**. The cathode **55** of the OLED **50**, which is formed as a thin, semi-transparent layer of Mg:Ag alloy, is deposited on the ITO layer **61**. The ETL/EL layer **54**, HTL **53**, protection layer **52** and ITO anode **51** are then deposited in sequence.

The combination of the ITO anode **51** and the bottom DBR structure **60** can provide good cavity and microcavity effect. In particular, if the thickness of the ETL/EL layer **54** is substantially equal to $\lambda/2n$, where λ is the wavelength of the emitted light and n is the refractive index of the ITO

anode layer **51** (which is approximately 2.0, relative to air), spectral narrowing is achieved with a considerable increase in the effective efficiency of the OLED.

To narrow the spectrum of the light emitted by the OLED of FIG. 5 even further, another DBR structure can be placed on top of the OLED **50**. This, however, requires that electrical access to the anode **51** of the OLED be provided from a side of the combined structure. As an alternative, such a top-side DBR can be replaced by a color filter layer consisting of, for example, an organic dye film.

FIG. 6 shows a display (represented as **101**) including a plurality of light emitting devices (represented as **102**). FIG. 7 shows a vehicle, television or computer (represented as **201**) incorporating a display (represented as **202**) including a light emitting device. FIG. 8 shows a printer, screen, sign, telecommunications device or telephone (represented as **301**) incorporating a light emitting device (represented as **302**).

The subject invention as disclosed herein may be used in conjunction with the subject matter of co-pending applications, "Novel Materials for Multicolor LED's," U.S. Ser. No. 08/771,815; "Electron Transporting and Light Emitting Layers Based on Organic Free Radicals," U.S. Ser. No. 08/774,120 "Multicolor Display Devices," U.S. Ser. No. 08/772,333; and "Red-Emitting Organic Light Emitting Devices (LED's), U.S. Ser. No. 08/774,087, each of said copending application being filed on the same date as the instant application, and being herein incorporated in their entirety by reference. The subject invention may also be used in conjunction with the subject matter of each of U.S. patent applications Ser. Nos. 08/354,674, which issued as U.S. Pat. No. 5,707,745, 08/613,207, which is now U.S. Pat. No. 5,703,436 08/632,316, which is now U.S. Pat. No. 5,721,160 08/632,322, which is now U.S. Pat. No. 5,757,026 and 08/693,359 and U.S. Provisional Patent applications Ser. Nos. 60/010,013 and 60/024,001, each of which is also herein incorporated in its entirety by reference.

What is claimed is:

1. An organic light emitting device, comprising:
 - a substrate with a pit having a slanted side wall formed into the top surface of the substrate,
 - a reflective first electrode formed on the top surface of the substrate,
 - a first organic layer formed on the first electrode,
 - a second organic layer formed on the first organic layer; and
 - a second electrode formed on the second organic layer,
 wherein at least one of the first and second organic layers emits light upon application of a voltage between the first and second electrodes and wherein the reflective first electrode on the slanted side wall causes light to be redirected in a direction substantially perpendicular to the substrate.
2. The light emitting device of claim 1, wherein the first electrode is a cathode and the second electrode is an anode.
3. The light emitting device of claim 1, wherein:
 - the first organic layer is an electroluminescent electron transporting layer,
 - the second organic layer is a hole transporting layer, and
 - the first organic layer emits light upon application of the voltage between the first and second electrodes.
4. The light emitting device of claim 1, wherein:
 - the first organic layer is an electron transporting layer,
 - the second organic layer is an electroluminescent hole transporting layer, and

the second organic layer emits light upon application of the voltage between the first and second electrodes.

5. The light emitting device of claim 1, wherein: the first organic layer is an electron transporting layer, the second organic layer is a hole transporting layer, and an electroluminescent layer is present between the electron transporting layer and the hole transporting layer, the electroluminescent layer emitting light upon application of the voltage between the first and second electrodes.

6. The light emitting device of claim 1, wherein the pit has a flat bottom surface with the slanted side wall forming an angle of approximately 135° with the flat bottom surface of the pit.

7. A display including a plurality of light emitting devices in accordance with claim 1.

8. A vehicle incorporating a display including the light emitting device of claim 1.

9. A television incorporating a display including the light emitting device of claim 1.

10. A computer incorporating a display including the light emitting device of claim 1.

11. A printer incorporating the light emitting device of claim 1.

12. A screen incorporating the light emitting device of claim 1.

13. A sign incorporating the light emitting device of claim 1.

14. A telecommunications device incorporating the light emitting device of claim 1.

15. A telephone incorporating the light emitting device of claim 1.

16. The light emitting device of claim 1 wherein the pit has a flat bottom surface forming an angle of approximately 135° with the slanted side wall.

17. The light emitting device of claim 1 wherein the pit has a semicircular cross section.

18. The light emitting device of claim 1 wherein the pit has an inverted triangular cross section.

19. An organic light emitting device, comprising:
 a substrate;
 a first electrode formed on a top surface of the substrate;
 a first organic layer formed on the first electrode;
 a second organic layer formed on the first organic layer;
 and
 a second electrode formed on the second organic layer, wherein the top surface of the substrate is substantially planar and the first electrode is formed between two interconnects covered with a polyimide material, the first electrode having a flat bottom surface and two side walls, each side wall forming an angle of approximately 135° with the bottom surface of the first electrode and wherein at least one of the first and second organic layers emits light upon application of a voltage between the first and second electrodes.

20. The light emitting device of claim 19, wherein the first electrode is a cathode and the second electrode is an anode.

21. The light emitting device of claim 19, wherein:
 the first organic layer is an electroluminescent electron transporting layer,
 the second organic layer is a hole transporting layer, and
 the first organic layer emits light upon application of the voltage between the first and second electrodes.

22. The light emitting device of claim 19 wherein:
 the first organic layer is an electron transporting layer,
 the second organic layer is an electroluminescent hole transporting layer, and
 the second organic layer emits light upon application of the voltage between the first and second electrodes.

23. The light emitting device of claim 19 wherein:
 the first organic layer is an electron transporting layer,
 the second organic layer is a hole transporting layer, and
 an electroluminescent layer being arranged between the electron transporting layer and the hole transporting layer the electroluminescent layer emitting light upon application of the voltage between the first and second electrodes.

24. An organic light emitting device, comprising:
 a substrate with a pit having a slanted side wall formed into the top surface of the substrate,
 a reflective metallic layer formed on the top surface of the substrate,
 a first electrode formed on the reflective metallic layer,
 a first organic layer formed on the first electrode,
 a second organic layer formed on the first organic layer,
 a second electrode formed on the second organic layer,
 wherein at least one of the first and second organic layers emits light upon application of a voltage between the first and second electrodes and wherein the reflective metallic layer on the slanted side wall causes light to be redirected in a direction substantially perpendicular to the substrate.

25. The light emitting device of claim 24, wherein the first electrode is an anode and the second electrode is a cathode.

26. The light emitting device of claim 24, wherein:
 the first organic layer is an electroluminescent hole transporting layer,
 the second organic layer is an electron transporting layer, and
 the first organic layer emits light upon application of the voltage between the first and second electrodes.

27. The light emitting device of claim 24, wherein:
 the first organic layer is a hole transporting layer,
 the second organic layer is an electroluminescent electron transporting layer, and
 the second organic layer emits light upon application of the voltage between the first and second electrodes.

28. The light emitting device of claim 24, wherein:
 the first organic layer is a hole transporting layer and the second organic layer is an electron transporting layer,
 an electroluminescent layer is present between the hole transporting layer and the electron transporting layer, and
 the electroluminescent layer emits light upon application of the voltage between the first and second electrodes.

29. The light emitting device of claim 24, wherein the pit has a flat bottom surface with the side wall forming an angle of approximately 135° with the flat bottom surface.

30. The light emitting device of claim 24 wherein the pit has a semicircular cross section.

31. The light emitting device of claim 24 wherein the pit has an inverted triangular cross section.

UNITED STATES PATENT AND TRADEMARK OFFICE
CERTIFICATE OF CORRECTION

PATENT NO. : 5, 834,893

DATED : November 10, 1998

INVENTOR(S) : Vladimir Bulovic, et al.

It is certified that error appears in the above-identified patent and that said Letters Patent is hereby corrected as shown below:

Column 1, line 50, after "metal" change "elect ode" to "electrode".

Column 1, line 67, change "disadvantage" to "disadvantages".

Column 4, line 27, insert a space between "Å" and "thick".

Column 5, line 26, change "OLEDS" to "OLEDs".

Column 8, line 33, after "5,703,436" insert ",,".

Column 8, line 34, after "5,721,160" insert ",,".

Column 8, line 64, insert a space between "claim 1," and "wherein".

Column 9, line 19, insert a space between "9." and "A".

Column 10, line 13, after "layer" (1st occurrence) insert ",,"

Signed and Sealed this

Seventh Day of September, 1999

Attest:



Q. TODD DICKINSON

Attesting Officer

Acting Commissioner of Patents and Trademarks

UNITED STATES PATENT AND TRADEMARK OFFICE
CERTIFICATE OF CORRECTION

PATENT NO. : 5,834,893
DATED : November 10, 1998
INVENTOR(S) : Vladimir Bulovic, et al

It is certified that error appears in the above-identified patent and that said Letters Patent is hereby corrected as shown below:

Column 3, line 5, change "DRIEF" to "BRIEF".

Signed and Sealed this
Twelfth Day of October, 1999

Attest:



Q. TODD DICKINSON

Attesting Officer

Acting Commissioner of Patents and Trademarks

UNITED STATES PATENT AND TRADEMARK OFFICE
CERTIFICATE OF CORRECTION

PATENT NO. : 5,834,893
DATED : November 10, 1998
INVENTOR(S) : Bulovic et al.

It is certified that error appears in the above-identified patent and that said Letters Patent is hereby corrected as shown below:

Column 1, line 4, insert

- GOVERNMENT RIGHTS

This invention was made with Government support under Contract No. F33615-94-1-1414 awarded by DARPA. The government has certain rights in this invention.--

Signed and Sealed this

Fifteenth Day of February, 2000

Attest:



Q. TODD DICKINSON

Attesting Officer

Commissioner of Patents and Trademarks