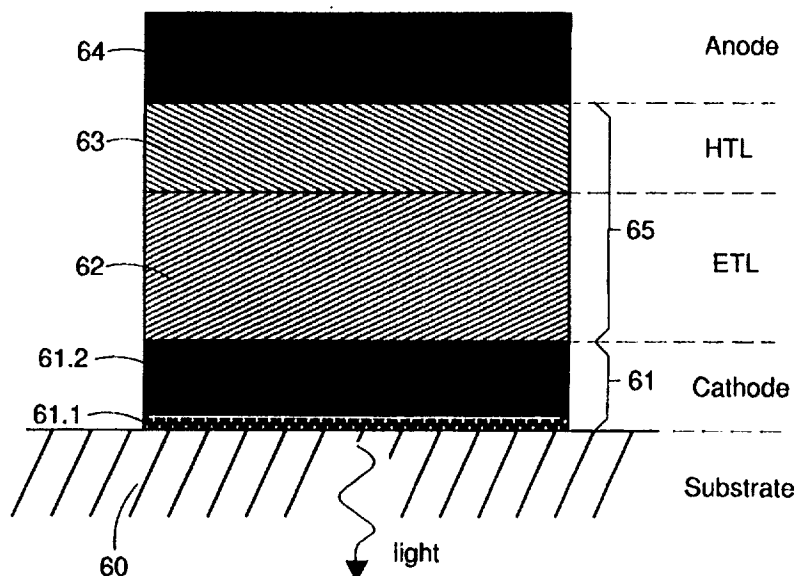


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(54) Title: GALLIUM NITRIDE BASED CATHODES FOR ORGANIC ELECTROLUMINESCENT DEVICES AND DISPLAYS

**(57) Abstract**

An organic light emitting device is provided which comprises a substrate (60), an anode electrode (64), a cathode (61), and an organic region (62, 63) in which electroluminescence takes place if a voltage is applied between said anode (64) and cathode (61). The cathode (61) comprises Gallium Nitride (GaN).

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DESCRIPTION

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Gallium Nitride Based Cathodes for Organic Electroluminescent Devices and Displays

TECHNICAL FIELD

10 The present invention pertains to organic electroluminescent devices, arrays, displays and methods for making the same.

BACKGROUND OF THE INVENTION

15 Organic electroluminescence (EL) has been studied extensively because of its possible applications in discrete light emitting devices, arrays and displays. Organic materials investigated so far can potentially replace conventional inorganic materials in many applications and enable wholly new applications. The ease of fabrication and extremely high degrees of
20 freedom in organic EL device synthesis promises even more efficient and durable materials in the near future which can capitalize on further improvements in device architecture.

Organic EL at low efficiency was observed many years ago in
25 metal/organic/metal structures as, for example, reported in Pope et al., Journal Chem. Phys., Vol. 38, 1963, pp. 2024, and in "Recombination Radiation in Anthracene Crystals", Helfrich et al., Physical Review Letters, Vol. 14, No. 7, 1965, pp. 229-231. Recent developments have been spurred largely by two reports of high efficiency organic EL. These are C.W. Tang et al.,
30 "Organic electroluminescent diodes", Applied Physics Letters, Vol. 51, No. 12, 1987, pp. 913-915, and by a group from Cambridge University in Burroughs et al., Nature, Vol. 347, 1990, pp. 539. Tang et al. made two-layer organic light emitting devices using vacuum deposited molecular dye

1 compounds, while Burroughs used spin coated poly(p-phenylenevinylene)
(PPV), a polymer.

The advances described by Tang and in subsequent work by the Cambridge
5 group, for example in "Efficient LEDs based on polymers with high electron
affinities", N. Greenham et al., Nature, Vol. 365, 1993, pp. 628-630, were
achieved mainly through improvements in the design of EL devices derived
from the selection of appropriate organic multilayers and contact metals.

10 Organic EL light emitting devices (OLEDs) function much like inorganic
LEDs, except that light is commonly extracted through a transparent
electrode deposited on a transparent glass substrate. The simplest possible
structure, schematically illustrated in Figure 1A, consists of an organic
emission layer 10 sandwiched between two electrodes 11 and 12 which
15 inject electrons (e^-) and holes (h^+), respectively. Such a structure has been
described in the above mentioned paper of Burroughs et al., for example.
The electrons and holes meet in the organic layer 10 and recombine
producing light. It has been shown in many laboratories, see for example:
"Conjugated polymer electroluminescence", D. D. C. Bradley, Synthetic
20 Metals, Vol. 54, 1993, pp. 401-405, and "Carrier tunneling and device
characteristics in polymer LEDs", I. D. Parker, Journal of Applied Physics,
Vol. 75, No. 3, 1994, pp. 1656-1666, that improved performance can be
achieved when the electrode materials are chosen to match the respective
molecular orbitals of the organic material forming the organic layer 10.
25 Such an improved structure is shown in Figure 1B. By choosing the
optimized electrode materials 13 and 14, the energy barriers to injection of
carriers are reduced, as illustrated. Still, such simple structures perform
poorly because little stops electrons from traversing the organic layer 10
and reaching the anode 14, or the holes from reaching the cathode 15.

30

Figure 2A illustrates a device with a large electron barrier 16, such that few
electrons are injected, leaving the holes no option but to recombine in the
cathode 15.

1 A second problem, illustrated in Figure 2B, is that the mobilities of
electrons and holes in most known organic materials, especially conductive
ones, differ strongly. Figure 2B illustrates an example where holes injected
from the anode 18 quickly traverse the organic layer 19, while the injected
5 electrons move much slower, resulting in recombination near the cathode
17. If the electron mobility in the organic layer 19 were larger than the
holes', recombination would occur near the anode 18. Recombination near
a metal contact is strongly quenched by the contact which limits the
efficiency of such flawed devices.

10

Tang, as shown in Figure 3, separated electron and hole transport functions
between separate organic layers, an electron transport layer 20 (ETL) and a
hole transport layer (HTL) 21, mainly to overcome the problems described
above. In "Electroluminescence of doped organic thin films", C.W. Tang et
15 al., Journal of Applied Physics, Vol. 65, No. 9, 1989, pp. 3610-3616, it is
described that higher carrier mobility was achieved in the two-layer design,
which led to reduced device series resistance enabling equal light output at
lower operating voltage. The contact metals 22, 23 could be chosen
individually to match to the ETL 20 and HTL 21 molecular orbitals,
20 respectively, while recombination occurred at the interface 24 between the
organic layers 20 and 21, far from either electrode 22, 23. As electrodes,
Tang used a MgAg alloy cathode and transparent Indium-Tin-Oxide (ITO) as
the anode. Egusa et al. in "Carrier injection characteristics of organic
electroluminescent devices", Japanese Journal of Applied Physics, Vol. 33,
25 No. 5A, 1994, pp. 2741-2745 have shown experimentally that the proper
selection of the organic multilayer can lead to a blocking of both electrons
and holes at an organic interface remote from either electrode. This effect
is illustrated by the structure of Figure 3 which blocks electrons from
entering the HTL 21 and holes from entering the ETL by a clever choice of
30 HTL and ETL materials. This feature eliminates non-radiative recombination
at the metal contacts as described in Figure 1A and also promotes a high
density of electrons and holes in the same volume leading to enhanced
radiative recombination.

1 With multilayer device architectures now well understood and commonly
used, the major performance limitation of OLEDs is the lack of ideal contact
electrodes. The main figure of merit for electrode materials is the position of
the bands relative to those of the organic materials (see Bradley and Parker
5 above for detailed discussion). In some applications it is also desirable for
the electrode material to be either transparent or highly reflective. The
electrode should also be chemically inert and capable of forming a dense
uniform film to effectively encapsulate the OLED. It is also desirable that the
electrode not strongly quench organic EL.

10

The choice of a good cathode electrode is particularly difficult. No material
has yet been identified which is transparent, conductive, chemically stable,
and a good electron injector for OLEDs. Good electron transporting organic
materials which are known have their lowest unoccupied molecular orbitals
15 (LUMO) matched only with metals having very low work functions. A low
work function in a metal is tantamount to high chemical reactivity. While,
e.g., Ca is very well matched in energy to an Alq3 (tris(8-hydroxyquinoline
aluminum)) electron transport layer, a Ca cathode survives intact only a
short time in air, leading to rapid device degradation. It is also likely that
20 such highly reactive metals undergo a chemical reaction with the nearby
organic materials which also could have negative effects on device
performance. Such a mechanism has been proposed by Parker in the above
cited reference to explain why Sm or Yb cathode OLEDs have poorer
performance than Ca cathode OLEDs despite the lower work function of Sm
25 and Yb compared to Ca. A low work function cathode metal approach
requires careful handling of the device to avoid contamination of the
cathode metal, and immediate, high quality encapsulation of the device if
operation in a normal atmosphere is desired. Even well encapsulated low
work function metal contacts are subject to degradation resulting from
30 naturally evolved gases from the organic LED materials caused by heating
during device operation.

1 On the other hand, the choice of a stable metal having a higher work
function, e.g. Al, dictates that the device can only be operated at high
voltages. High voltage is necessary because electron injection from Al into,
e.g., Alq3 is field assisted. The high operating voltage reduces device
5 efficiency due to increased ohmic losses. In addition, the higher electrical
fields present at increased voltages also are likely to degrade the device
materials more rapidly by driving interdiffusion or exciting parasitic
chemical reactions or recombination processes. Al contacts, of lesser
reactivity compared to Mg or Ca, have still been observed to degrade
10 during OLED operation, see e.g. L. M. Do et al., "Observation of
degradation processes of Al electrodes in organic EL devices by
electroluminescence microscopy, atomic force microscopy, and Auger
electron microscopy", Journal of Applied Physics, Vol. 76, No. 9, 1994, pp.
5118-5121.

15 Many approaches have been attempted in order to solve the problem of
cathode electrode instability, degradation and high injection voltage. A
common approach is the use of a low work function metal subsequently
buried under a thicker metal coating. In this case, pinholes in the metal still
20 provide ample pathways for oxygen and water to reach the reactive metal
below, as is described in: Y. Sato et al., "Stability of organic
electroluminescent diodes", Molecular Crystals and Liquid Crystals, Vol.
253, 1994, pp. 143-150 and J. Kido et al., "Bright organic electroluminescent
devices with double-layer cathode", IEEE Transactions on Electron Devices,
25 Vol. 40, No. 7, 1993, pp. 1342-1344. Furthermore, such contacts are
degraded by evolved gases from and reactions with the OLED constituent
materials. The overall lifetime of OLEDs using this approach is limited and
extensive encapsulation is required.

30 I. D. Parker and H. H. Kim, "Fabrication of polymer light-emitting diodes
using doped silicon substrates", Applied Physics Letters, Vol. 64, No. 14,
1994, pp. 1774-1776, showed that, depending on the semiconductor doping,
Si/SiO₂ is capable of either hole or electron injection. Si electrodes, due to

1 the small bandgap and moderate work function of Si, have both a barrier to
electron and hole injection into organic LED materials, and therefore
represent no marked improvement over conventional metals. Parker and
Kim avoided this by adding a SiO₂ interlayer between the Si contact and
5 OLED. While the voltage drop across the SiO₂ insulator permitted the Si
bands to line up with their organic molecular orbital counterpart, electrons
were not directly injected, rather forced to tunnel through the SiO₂
insulator. Such OLEDs had turn-on voltages of > 10 V, too high for efficient
device operation.

10

On the anode side, ITO, which has been preferred primarily for its high work
function and its properties as a transparent conductor, is also not ideal.
Parker, in the reference cited above, has shown that the replacement of ITO
with higher work function Au yields a two-fold improvement in device
15 efficiency. This work reveals that an undesirable barrier to hole injection
exists between ITO and preferred HTL materials. There are also questions
about the chemical reactivity of ITO contacts. Oxidation of, and In diffusion
into the organic layers, arising from the proximity of the ITO contact has
been speculated to contribute to OLED degradation. ITO is also
20 polycrystalline, and its numerous grain boundaries provide ample pathways
for impurity diffusion.

The lack of inert, stable, energetically matched, and transparent electrode
materials for low voltage, efficient and stable OLED operation remains a
25 major obstacle to OLED development.

Organic LEDs have great potential to outperform conventional inorganic
LEDs in many applications. One important advantage of OLEDs and devices
based thereon is price since they can be deposited on large, inexpensive
30 glass substrates, or a wide range of other inexpensive transparent,
semitransparent or even opaque crystalline or non-crystalline substrates at
low temperature, rather than on expensive crystalline substrates of limited
area at comparatively higher growth temperatures (as is the case for

1 inorganic LEDs). The substrates may even be flexible enabling pliant OLEDs
and new types of displays. To date, the performance of OLEDs and devices
based thereon is inferior to inorganic ones for several reasons:

- 5 1. High operating voltage: Organic devices require more voltage to inject
and transport the charge to the active region (emission layer) which in
turn lowers the power efficiency of such devices. High voltage results
from the need for high electric fields to inject carriers over energy
barriers at the electrode/organic interfaces, and from the low mobility of
10 the carriers in the organic transport layers (ETL and HTL) which leads to
a large ohmic voltage drop and power dissipation.
2. Low brightness: Today's OLEDs can produce nearly as many photons
per electron as common inorganic LEDs, i.e. their quantum efficiency is
15 good. OLEDs lag inorganic LEDs in brightness mainly because
comparatively little charge can be conducted through the resistive
transport layers (HTL or ETL). This well known effect is referred to as
Space Charge Limited Current. Simply put, due to the low mobility of
carriers in organic materials, a traffic jam develops which restricts the
20 flux of electrons and holes reaching the emission layer. Better emitter
materials cannot offer greatly improved brightness until high
conductance transport layers are also available.
3. Reliability: Organic LEDs degrade in air and during operation. Several
25 problems are known to contribute.
 - A) Efficient low field electron injection requires low work function
cathode metals like Mg, Ca, Li etc. which are all highly reactive in
oxygen and water. Ambient gases, and gases coming out of the organic
materials during ohmic heating degrade the contacts.
 - 30 B) Conventional AgMg and ITO contacts still have a significant
barrier to carrier injection in preferred ETL and HTL materials,
respectively. Therefore, a high electric field is needed to produce
significant injection current. Stress from the high field and ohmic

1 heating at the resistive electrode/organic interface contribute to device degradation.

C) The high resistance of carrier transport layers heats the device under operation.

5 D) Thermal stability of most OLED materials is poor making them sensitive to heating. Upon heating, many amorphous organic materials crystallize into grains. The crystallites have less volume and pack less uniformly than the amorphous solid. The resulting gaps and odd shapes of the crystallites make conduction from one crystallite to the next difficult, increasing resistance and heating in a positive feedback loop, while opening further channels for gaseous contaminants to penetrate, or for neighboring materials to diffuse.

10 4. Poor chemical stability: Organic materials commonly used in OLEDs are vulnerable to degradation caused by reaction with and diffusion of contact electrode materials and the ambient atmosphere.

OLEDs are mainly limited by their contacts and transport layers, and feedback from the transport layer heating. It is thus highly desirable to replace the low work function metal based cathodes with stable, possibly transparent cathode characterized by barrierless charge injection into OLEDs. A transparent cathode provides the additional advantage of allowing conventional ITO anodes to be replaced with improved anodes.

25 However, present day solutions inhibit performance and degrade device reliability. The price of distancing the active layer from the metal contacts for higher recombination efficiency are ohmic voltage drops across the HTL/ETL, leading to heating and power consumption. Low work function metals are unstable and unreliable.

30

As can be seen from the above examples and the description of the state of the art the contact materials need to be improved to realize OLEDs and displays based thereon with superior characteristics.

1 It is an object of the present invention to provide new and improved organic EL devices, arrays and displays based thereon.

It is a further purpose of the present invention to provide new and improved
5 organic EL devices, arrays and displays based thereon with improved efficiency, lower operating voltage, and increased reliability.

It is a further object to provide a method for making the present new and improved organic EL devices, arrays and displays.

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SUMMARY OF THE INVENTION

The above objects have been accomplished by providing an OLED having a cathode comprising gallium nitride (GaN) wide bandgap semiconductor.

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The inventive approach capitalizes primarily on the favorable conduction band energy of GaN, as well as its good conductivity, transparency in the visible spectrum, chemical inertness, hardness, and ability to be deposited in the amorphous state at extremely low temperatures on glass, organic thin films, or other amorphous or crystalline substrates. Our experiments have shown that GaN is conductive, even when deposited at room temperature in the amorphous state, highly transparent in the visible spectrum, and has a favorable conduction band alignment for electron injection into the LUMOs of preferred OLED materials. Furthermore, GaN is an excellent encapsulant for OLEDs due to the extremely low diffusivity of impurities in GaN and the nearly amorphous state of material deposited at low temperature. In addition, the considerable strength of the Ga-N chemical bond makes GaN chemically inert, even capable of resisting the attack of highly corrosive acids and bases. We have experimentally observed that GaN - having all of the above favorable properties - can be deposited onto glass, or even directly onto an OLED multilayer structure, and produces a device with improved performance and stability.

20

In one embodiment of the present invention, a single or multi-layer OLED structure having a GaN cathode directly in contact with the corresponding organic layer, and a conventional opposite contact electrode is envisioned.

25

In another embodiment of the present invention, an OLED structure having an (Al,In)GaN cathode directly in contact with the corresponding organic layer, and a conventional opposite contact electrode is envisioned. The purpose of alloying the GaN cathode with small amounts ($<20\%$) of AlN is to finely tune the position of the cathode conduction band to the corresponding organic material molecular orbital. The purpose of alloying

30

1 the GaN with InN is to improve the ohmic contacts between the cathode and the outer cathode layer(s).

5 In yet another embodiment of the present invention, an OLED in which a GaN cathode, preferably an AlGaInN cathode, is separated from the nearest organic layer by a thin metal interlayer, is envisioned. The metal can be selected for its transparency, work function, or properties as a diffusion barrier between the organic materials and GaN, and serves the purpose of further improving the stability or electron injection of the GaN/organic interface.

10 In yet another embodiment of the present invention, an OLED in which a GaN cathode, preferably an AlGaInN cathode, is in direct contact to the nearest organic layer, but has a thin embedded metal interlayer very near to the GaN/organic interface. The metal can be selected for its work function, properties as a diffusion barrier between the organic materials and GaN, or transparency, and serves the purpose of further improving the stability or electron injection of the GaN/organic interface.

15 20 The introduction of a cathode comprising GaN leads to the following advantages:

1. Low voltage carrier injection is realized through the highly favorable band energies of GaN with respect to preferred OLED materials.
- 25 2. GaN is highly transparent to visible light. This adds flexibility in the choice of anode designs, e.g. the anode can be opaque.
3. GaN is chemically inert and thermally stable and therefore has no undesirable solid state interactions with the organic layers with which it is in contact or close proximity.
- 30

- 1 4. GaN is an outstanding encapsulant and mechanical protectant material
for OLEDs, due to its nearly amorphous state, hardness and low
impurity diffusion constants.
- 5 5. GaN can be deposited at conditions required for OLED formation (e.g.
low temperature, amorphous substrates, minimum damage to the
growth surface) in a conductive state.
- 10 6. GaN, as a semiconductor, quenches optical recombination in nearby
organic layers less strongly than metals enabling reduced transport
layer thicknesses.

There are four preferred GaN-based cathodes for OLEDs. In each case, the
device enjoys all of the advantages tabulated above.

15

1. GaN/Organic Cathode: The GaN is in direct contact with the electron
transporting OLED layer. The GaN may be deposited onto the organic
material or the organic material may be deposited onto the GaN.
- 20 2. InGaN/GaN/AlGaIn/organic Cathode: The AlGaIn or GaN is in direct
contact with the electron transporting OLED layer. Small amounts
($<20\%$) of AlN tune the (Al,In)GaN conduction band to precisely match
the organic material. InGaIn or GaN is furthest from the organic
material and facilitates lateral conduction or ohmic contact formation to
25 the GaN based cathode. The cathode may be deposited onto the
organic material or the organic material may be deposited onto the
cathode.
3. (Al,In)GaN/Metal/Organic Cathode: The GaN or (Al,In)GaN is separated
30 from the electron transporting OLED layer by a thin metal layer. The
thickness of the metal layer can range between a partial monolayer to
20 nm. Either the cathode or the organic layer can be deposited first.

- 1 4. (Al,In)GaN/Metal/(Al,In)GaN Organic Cathode: The GaN or (Al,In)GaN is
in direct contact with the electron transporting OLED layer, and
encapsulates a thin metal layer a short distance (< 50 nm) from the
cathode/organic interface. The thickness of the metal layer can range
5 between a partial monolayer and 50 nm. Either the cathode or the
organic layer can be deposited first.

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DESCRIPTION OF THE DRAWINGS

The invention is described in detail below with reference to the following schematic drawings:

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FIG. 1A shows a known OLED having an emission layer and two electrodes.

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FIG. 1B shows another known OLED having an emission layer and two metal electrodes, with work functions chosen such that the energy barriers for carrier injection are reduced.

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FIG. 2A shows another known OLED having an emission layer and two metal electrodes, the work function of the anode being chosen such that the energy barrier for hole injection is low, whereas the work function of the cathode poorly matches the emission layer yielding little electron injection and little radiative recombination in said emission layer.

20

FIG. 2B shows another known OLED having an emission layer with lower electron mobility than hole mobility such that the recombination occurs close to the cathode where it is quenched.

25

FIG. 3 shows another known OLED having an electron transport layer and hole transport layer.

30

FIG. 4 shows an optical absorption spectrum of a GaN/glass thin film. The onset of absorption occurs around 360nm in the near ultraviolet, which is responsible for the high transparency of GaN grown at low substrate temperatures on all types of substrates.

1 **FIG. 5** shows the band structure measured by ultraviolet
photoemission spectroscopy for a GaN/Alq3 heterojunction. Experimental error is included in the Alq3 bands as drawn. To
5 within experimental error, the lowest unoccupied molecular orbital (LUMO) of Alq3 lies at equal or lower energy compared to the GaN conduction band minimum meaning that electron injection from GaN to Alq3 is barrierless.

10 **FIG. 6** shows a cross section of the first embodiment of the present invention in which a GaN cathode is deposited on the substrate before the organic layer stack. Light is emitted through the transparent cathode and glass substrate into the plane below the substrate.

15 **FIG. 7** shows a cross section of the second embodiment of the present invention in which a GaN cathode is deposited on top of the organic layer stack. Light is emitted through the transparent cathode into the plane above the substrate.

20 **FIG. 8** shows a cross section of the third embodiment of the present invention in which an AlGaInN cathode is deposited on top of the organic layer stack. Light is emitted through the ITO anode and glass substrate into the plane below the substrate. If a transparent outer cathode metal other than Al would be
25 chosen, the cathode would also be transparent, and light would be emitted into both planes above and below the substrate.

30 **FIG. 9** shows a cross section of the fourth embodiment of the present invention in which a GaN cathode deposited on top of the organic layer stack is separated by a thin metal interlayer. The metal serves to either improve injection, protect the organic during GaN deposition, or act as a diffusion barrier. Light is

1 emitted through the transparent cathode plane above the substrate.

5 **FIG. 10** shows a cross section of the fifth embodiment of the present invention in which a GaN cathode encapsulates a thin metal layer which is situated very near to the organic layer stack. The thin GaN layer permits electrons to pass freely from the metal to the organic layer, either by tunneling or thermionic emission, while chemically and physically isolating the metal from the organic. Light is emitted into both the planes above and below the substrate.

10 **FIG. 11** shows a cross section of a display or array according to the present invention. The transparent GaN based top cathode permits an opaque Si substrate to be chosen. The Si substrate can be an integrated circuit providing the display function to the OLED array deposited on top of it.

15 **FIG. 12** shows a cross section of a display or array according to the present invention in which a GaN based cathode is deposited onto an opaque Si substrate. The GaN cathode provides a stable cathode which can withstand typical handling and processing of the Si wafer.

20 **FIG. 13** shows a cross section of a display or array according to the present invention in which a transparent GaN based cathode down geometry is used on a glass substrate. Light is emitted in the plane below the glass substrate.

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GENERAL DESCRIPTION

GaN is an ideal material for electron injection into OLEDs, based both on what is known of the material in the literature, and what we have discovered in our laboratory. The physical properties of GaN are catalogued in: S. Strite and H. Morkoc, "GaN, AlN and InN: a review", Journal of Vacuum Science and Technology B, Vol. 10, 1992, pp. 1237-1266 and "Properties of Group III Nitrides", edited by James H. Edgar, (The Institution of Electrical Engineers, London 1994). The properties of GaN as a transparent conductor have been described by H. Sato et al., "Transparent and conductive GaN thin films prepared by an electron cyclotron resonance plasma metalorganic chemical vapor deposition method", Journal of Vacuum Science and Technology A, Vol. 11, No. 4, 1993, pp. 1422-1425. As reviewed above, an ideal contact electrode material should be characterized by:

15

1. Depositability onto organic layers, amorphous, crystalline or polycrystalline substrates at low temperatures with little damage to the underlying material.
- 20 2. Favorable energy band levels for injection of charge into preferred OLED materials.
3. Sufficient electrical conductivity so that total device series resistance is unaffected by the electrode.
- 25 4. High transparency in the visible spectrum (for low quenching and flexibility in light extraction).
5. Chemical inertness
- 30 6. Low diffusivity of impurities
7. Mechanical hardness

- 1 GaN can be deposited at low temperatures via magnetron sputtering, laser
ablation, plasma enhanced molecular beam deposition (PEMBD) or other
related techniques in which the energy required to create a reactive
nitrogen radical is supplied from some external stimulus, and not thermal
5 energy at the substrate. PEMBD, in which thermally evaporated Ga atoms
react with low kinetic energy nitrogen radicals at the substrate surface, is
our preferred method due to the small amount of chemical and/or kinetic
damage endured by the substrate and the large supply of reactive nitrogen
species created by the plasma. Ga can be supplied from thermally
10 evaporated elemental metal, or from a Ga containing compound or gas.
Active N is supplied by the plasma excitation which excites and cracks a N
bearing gas, typically N_2 , NH_3 , hydrazine. Using this method, undoped GaN
has a resistivity of roughly 10 Ohm-cm when grown at room temperature.
OLEDs incorporating a GaN cathode grown onto the organic layer stack
15 show comparable properties to inverted structures in which the GaN
cathode is grown first, demonstrating that GaN can be grown by the PEMBD
technique without damaging the organic layer below. The temperature at
which the GaN is grown should be below 150 degree centigrade.
- 20 We have studied the band structure of GaN deposited onto glass at low
temperature. Figure 4 is a transmission spectrum of one such thin film.
These data indicate that low temperature amorphous GaN, much like
crystalline GaN, has a wide bandgap energy of 3.3 - 3.4 eV, making it highly
transparent to visible light. In order to determine the energy position of the
25 GaN conduction and valence bands relative to common OLED materials, a
clean GaN surface was prepared onto which a thin layer of Alq3 was
vacuum deposited. In this arrangement, Ultraviolet Photoemission
Spectroscopy can resolve the relative positions in energy of the GaN
valence band and the Alq3 highest occupied molecular orbital (HOMO).
30 These data, depicted in Figure 5 and combined with our knowledge of the
GaN and Alq3 bandgap, indicate that the GaN conduction band is positioned
at equal or higher energy with respect to the Alq3 lowest unoccupied
molecular orbital (LUMO), meaning that electron injection from GaN into

1 electron transporting Alq3 can proceed with no or even a negative intermediate barrier.

Further confirmation of the favorable energy positioning of the GaN
5 conduction band comes from measurements of actual OLED device structures, e.g. a GaN cathode structure having the following layer sequence from the glass substrate up: Glass/ITO/CuPc/NPB/Alq3/GaN/InGaN/Al. Please note that the abbreviation NPB means: N,N'-diphenyl-N,N'-bis-(4-phenylphenyl)-1,1'-biphenyl-4,4'-diamine. This
10 device performed better than conventional Glass/ITO/CuPc/NPB/Alq3/MgAg OLED devices, both in terms of operating voltage and external efficiency. InGaN was added to facilitate ohmic contact from the Al to the GaN. Polymer based OLEDs also show improved device performance when GaN cathodes are formed, which is expected since injection occurs via the same
15 mechanisms in polymers as molecular organic compounds.

Our experimental results have shown that GaN fulfills the first four points of the above list describing an ideal contact electrode. That GaN fulfills the next three points (5-7) is apparent from the technical literature on GaN
20 which is readily available, e.g. in the above referenced review paper by Strite and Morkoc or the book entitled "Properties of Group III Nitrides."

In order to overcome the problems of conventional metal cathodes for discrete light emitters, light emitting arrays and display applications.
25 improved structures which capitalize on the favorable physical properties of GaN, as illustrated in Figures 6-10, are provided, enabling new array and display applications as illustrated in Figures 11-13.

Several embodiments of improved OLEDs incorporating GaN contact
30 electrodes are now detailed in connection with Figures 6-10.

The simplest embodiment of a GaN cathode OLED, already improved with respect to the state of the art is depicted in Figure 6. From the substrate

up, listed in the order of deposition, is a glass/GaN/ETL/HTL/Metal OLED structure. In addition to the lower barrier to electron injection afforded by the cathode 61 comprising GaN formed on the glass substrate 60, the ETL 62 thickness may be reduced as a result of reduced optical quenching and the conventional ITO anode can be replaced by a higher work function metal since the anode 64 must no longer serve as the transparent contact. We note here that the structure depicted in Figure 6 might also benefit from the addition of an additional layer 61.1 (e.g. ITO) between the GaN 61.2 and glass 60 to lower the lateral sheet resistance of the cathode 61. Finally, any substrate, even an opaque one, can replace the glass substrate 60 depicted. In this case, the preferred embodiment would have a transparent top contact 64, e.g. ITO in the case of a cathode 61 comprising GaN. The organic region 65 of the first embodiment comprises an ETL 62 and HTL 63. It is to be noted that the present Figure and all other Figures are not drawn to scale.

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Table 1: Exemplary details of the first embodiment				
Layer	No.	Material	Width	present example
substrate	60	glass	0.1mm-5mm	1mm
outer cathode	61.1	ITO	10-300 nm	50 nm
cathode	61.2	GaN	10-300nm	50nm
ETL and EL	62	Alq3	20-1000nm	80nm
HTL	63	TAD	5-500nm	50nm
anode	64	Au	10-2000nm	50nm

A second embodiment of a GaN cathode device is depicted in Figure 7. From the substrate 70 up, listed in the order of deposition, is a

1 glass/Metal/HTL/EL/ETL/GaN OLED structure. The major difference between
Figure 7 and Figure 6 is that the cathode 75 comprising GaN is deposited
last on top of the organic layer stack 72-74, which in this case includes a
separate emission layer 73 (EL) as is sometimes practiced in the art. We
5 note that structures in which the GaN layer 75.1 being part of the cathode 75
is directly deposited onto the OLED stack 72-74 have similarly improved
performance in comparison to structures such as that depicted in Figure 6.
ITO might be substituted for the metal anode 71 of Figure 7 if that contact
needs to be transparent. Also, the cathode 75 might comprise additional
10 layer or layers, e.g. an InGaN layer 75.2, an ITO layer 75.3, might be grown
on top of the GaN layer 75.1 in order to reduce the lateral sheet resistance
of the contact and improve electron injection from the ITO 75.3 into the GAN
75.1. Any substrate other than glass can be chosen, even an opaque one. In
the latter case, the cathode 75 is preferably designed to be fully transparent
15 for ease of light extraction. The organic region 75 of the second
embodiment comprises an ETL 74, a layer 73 suited for electroluminescence
(EL) and HTL 72.

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Table 2: Exemplary details of the second embodiment				
Layer	No.	Material	Width	present example
substrate	60	glass	0.1mm-5mm	1mm
anode	71	Ni	10-300 nm	50 nm
HTL	72	TAD	5-500nm	50nm
EL	73	coumarine-doped Alq3	20-1000 nm	70 nm
ETL	74	Alq3	1-100nm	20nm
cathode contact	75.1	GaN	10-2000nm	50nm
ohmic contact layer	75.2	InGaN	10-2000nm	50nm
outer cathode	75.3	ITO	10-2000nm	50nm

A third embodiment of the present invention is depicted in Figure 8. From the substrate 80 up, listed in the order of deposition, this embodiment comprises glass/ITO/HTL/ETL/(Al,In)GaN OLED structure. In this case, the GaN has been alloyed with AlN to match the cathode conduction band to the LUMO of the ETL. The improved alignment may be necessary if an ETL is selected which has a higher LUMO energy than the GaN CB. We note that these concepts are equally valid for cathode down structures in which the GaN cathode is grown prior to the organic layers and top anode. GaN has been combined with ITO to improve ohmic contact between the cathode 84.1 and outer cathode 84.3. The organic region 85 of the third embodiment comprises a combined ETL/EL layer 83 and a HTL 82.

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Table 3: Exemplary details of the third embodiment				
Layer	No.	Material	Width	present example
substrate	80	glass	0.1mm-5mm	1mm
anode	81	ITO	10-300nm	50nm
HTL	82	TAD	5-500nm	50nm
ETL and EL	83	Oxadiazole	50-1000nm	70nm
cathode	84.1	$\text{Al}_{0.1}\text{Ga}_{0.9}\text{N}$	10-2000nm	50nm
ohmic contact layer	84.2	InGaN	10-2000nm	50nm
outer cathode	84.3	Al	10-2000nm	50nm

A fourth embodiment of the present invention is depicted in Figure 9. From the substrate 90 up, listed in the order of deposition, is a glass/ITO/HTL/ETL/TM/GaN OLED structure. In this case, the thin metal (TM) 94.1 is chosen either for its transparency, low work function or properties as a chemical, diffusion or protective barrier between the organic ETL and GaN 94.2. The TM may be helpful in improving the alignment of the GaN 94.2 CB to the LUMO of the ETL 93, in which case GaN 94.2 doubles as both an electron injector and an encapsulant for the OLED and TM. The TM 94.1 may improve reliability by inhibiting chemical reactions or diffusion between the organic and the GaN layer 94.2 during or after growth, or as a protective barrier to shield the ETL 93 from degradation caused by the GaN 94.2 deposition. We note that these concepts are equally valid for cathode down structures in which the GaN then the TM are grown prior to the organic layers and top contact, and also

1 for (Al,In)GaN alloys according to the third embodiment. The organic
region 95 of the fourth embodiment comprises a combined ETL/EL layer 93
and a HTL 92.

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Table 4: Exemplary details of the fourth embodiment				
Layer	No.	Material	Width	present example
substrate	90	glass	0.1mm-5mm	1mm
anode	91	Pt	10-300nm	50nm
HTL	92	TAD	5-500nm	50nm
ETL and EL	93	Alq3	20-1000nm	70nm
thin metal	94.1	Ca	0.01-10nm	1nm
cathode	94.2	GaN	10-2000nm	50nm
ohmic contact layer	94.3	InGaN	10-2000nm	50nm
outer cathode	94.4	ITO	10-2000nm	50nm

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Finally, Figure 10 depicts an OLED structure in which a GaN or (Al,In)GaN cathode encapsulates an embedded TM interlayer near the cathode/organic interface. The thin GaN layer between the TM and the organic stack serves as a chemical and diffusion barrier to prevent mixing and reactions between the metal and organic materials. The GaN layer
30 between the TM and the organic is thin enough to permit electrons to easily pass from the TM to the organic region by either tunneling or thermionic emission. We note that this concept is equally valid for both

1 cathode down and up architectures, as well as for (Al,In)GaN cathodes.
The organic region 105 of the fourth embodiment comprises a combined
ETL/EL layer 103 and a HTL 102.

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Table 5: Exemplary details of the fifth embodiment				
Layer	No.	Material	Width	present example
substrate	100	glass	0.1mm-5mm	1mm
sub-anode	101	ITO	10-300nm	50nm
HTL	102	TAD	5-500nm	50nm
ETL and EL	103	Alq3	20-1000nm	70nm
cathode interlayer	104.1	GaN	1-50nm	10nm
TM	104.2	Li	1-20nm	2nm
cathode	104.3	GaN	10-200nm	50nm
ohmic contact	104.4	InGaN	10-200nm	50nm
outer cathode	104.5	ITO	10-2000nm	50nm

In the following, some display embodiments, based on and enabled by the present invention, are disclosed.

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It would be advantageous if one could integrate OLEDs onto Si substrates because prior to OLED deposition, the substrate could be fabricated to contain active Si devices, such as for example an active matrix, drivers, memory and so forth. Such a structure can be a very inexpensive small

1 area organic display with high resolution and performance realized in the Si. An OLED, OLED arrays or an OLED display may either be grown directly on such a Si substrate carrying Si devices, or it may be fabricated separately and flipped onto the Si substrate later. A problem is the Si
5 metallization. Traditional OLED cathode metals are not stable in Si processes or air. Another problem is that a transparent top contact is needed because Si is not a transparent substrate. The present invention offers a solution to these problems. The disclosed GaN based cathode permits a stable, low voltage contact to be formed on top of the standard Si
10 process metallizations, and are therefore compatible with OLED technology.

An organic array or display structure formed on a Si substrate is illustrated in Figure 11 and described in the following. This display comprises a Si
15 substrate 110 which has integrated circuits comprising active and/or passive devices such as memory cells, drivers, capacitors, transistor etc. (these devices are not shown). On top of the Si integrated circuit, a stable OLED anode (e.g. ITO, Au, Pt, Ni, Cr) material 111 is patterned to connect the Si devices to the OLEDs 112. An OLED, in the cathode-up geometry is
20 deposited on the patterned anodes 111 and Si substrate 110. Finally, a GaN-based cathode 113 is provided. It is to be noted that no details of the OLED(s) are shown for sake of simplicity, but the OLED may be any color including blue or white. For the examples of blue and white OLEDs respectively, full color might be realized by patterning a color conversion
25 dye array or color filter array on top of the cathode.

For example, an Al-metallized Si chip 110 on which ITO anodes 111 are patterned may serve as substrate for an OLED array or display 112. One such OLED comprises (from the bottom to the top): a stable anode layer,
30 e.g. ITO 111, a HTL, an organic doped or undoped active region, an ETL, and a cathode 113 which comprises GaN. This cathode 113 may for example be composed of the following stack of 'layers': TM/GaN/InGaN/ITO.

1 The organic region of the present devices may - in addition to charge transport layers if needed at all - either comprise:

- a stack of more than one organic emission layers (EL), or
- 5 • an organic compound doped with one or more impurities, organic or inorganic, chosen to dominate and enhance the electroluminescence, or
- 10 • a stack of more than one organic emission layer, some of which may be doped to dominate or enhance the electroluminescence of that particular organic emission layers, or
- 15 • a stack of more than one organic layer, in which the role of one or more of said organic layers is to electrically confine one or more carrier types to improve the emission of an adjacent organic layer.

Another array or display embodiment, where the OLEDs 122 have the anode up, is illustrated in Figure 12. In this Figure, OLEDs 122 on top of a Si substrate 120 are schematically shown. In this case, the Si substrate 120 is partially covered by Al metal electrodes 121.1 which inject charge into the GaN-based cathodes 121. Other areas 120.1 do not conduct current. In addition, the Si IC substrate 120 could be planarized during the back end of the Si processing. This approach lowers processing cost because a blanket GaN-based cathode 121 can be deposited immediately before OLED deposition, and does not require additional patterning. As discussed above, this is possible because the intended vertical current must traverse a distance much smaller than the spacings between Al contact pads 121.1. Simple geometry insures that little crosstalk will occur, even when the anode 123 is common to all devices, as is shown in Figure 12. The top anode 123 must be transparent since the Si substrate 120 is opaque to most visible light. Color could also be conveniently incorporated into the embodiment shown in Figure 12, as with Figure 11 also, by means of color

1 fillers and/or converters 124 which are deposited or patterned onto the transparent top contact.

5 The anode up embodiment on Si of Figure 12 may have advantages compared to the cathode up version of Figure 11 which arise from the generally higher hole mobilities in preferred HTL layers compared to electron mobilities in preferred ETL layers. If any damage to the upper organic layer occurs during electrode deposition, or contamination diffuses through the electrode and degrades the HTL, it could still have a higher mobility than the buried and ungraded ETL, and therefore not be the limiting factor in overall current conduction. Simply put, since the HTL initially outperforms the ETL in known OLED devices, the device is less sensitive to the initial stages of degradation of the HTL than the ETL.

15 Another possible display embodiment, illustrated in Figure 13, is described below. This display comprises a transparent substrate 130 on top of which amorphous-Si or poly-Si structures are formed using the same technology developed for active matrix liquid crystal displays. Usually the Si is structured to provide thin-film-transistors 131 (TFTs) and other devices, to produce an active matrix. The Si devices 131 formed may then be covered or planarized by special layers 134. Color filters or color converters 132 can be provided, in addition, if the OLEDs 135 emit white or blue light, respectively. The Si devices 131 include structured GaN-based cathodes 133, for example, onto which the OLEDs 135 can be deposited. An advantage of this approach is that entrenched active matrix liquid crystal display (AMLCD) technology can be leveraged in combination with OLEDs to realize inexpensive, high performance AM displays over large areas. Furthermore, clever design permits light to be emitted through the glass substrate 130 so no transparent top contact (anode 136) is needed. The anode 136 may be covered by a cap layer 137.

In the following some examples of the different organic materials which can be used are given.

1 Electron transport/Emitting materials:

Alq₃, Gaq₃, Inq₃, Scq₃, BAlq₃ (q means 8-hydroxyquinoline) and other
 8-hydroxyquinoline metal complexes such as Znq₂, Beq₂, Mgq₂, ZnMq₂,
 BeMq₂, and AlPrq₃, for example. These materials can be used as ETL or
 5 emission layer. Other classes of electron transporting materials are
 deficient nitrogen containing systems, for example oxadiazoles like PBD
 (any many derivatives), triazoles, for example TAZ (1,2,4-triazole). These
 functional groups can also be incorporated in polymers, starburst and
 spiro compounds. Further classes are materials containing pyridine,
 10 pyrimidine, pyrazine and pyridazine functionalities. Finally, materials
 containing quinoline, quinoxaline, cinnoline, phthalazine and quinazoline
 functionalities are well known for their electron transport capabilities.
 Other materials are cyano-substituted polymers, didecyl sexithiophene
 (DPS6T), bis-triisopropylsilyl sexithiophene (2D6T), Azomethin-zinc
 15 complexes, pyrazine (e.g. BNVP), strylnanthracent derivatives (e.g. BSA-1,
 BSA-2), non-planar distyrylarylene derivatives, for example DPVBi (see C.
 Hosokawa and T. Kusumoto, International Symposium on Inorganic and
 Organic Electroluminescence 1994, Hamamatsu, 42), cyano PPV (PPV
 means poly(p-phenylenevinylene)) and cyano PPV derivatives.

20 The following materials are particularly well suited as

Emission layers and Dopants:

Anthracene, pyridine derivatives (e.g. ATP), Azomethin-zinc complexes,
 25 pyrazine (e.g. BNVP), strylnanthracent derivatives (e.g. BSA-1, BSA-2),
 Coronene (also suited as dopant), Coumarin (also suited as dopant), DCM
 compounds (DCM1, DCM2; both also suited as dopants), distyryl arylene
 derivatives (DSA), alkyl-substituted distyrylbenzene derivatives (DSB),
 benzimidazole derivatives (e.g. NBI), naphthostyrylamine derivatives (e.g.
 30 NSD), oxadiazole derivatives (e.g. OXD, OXD-1, OXD-7),
 N,N,N',N'-tetrakis(m-methylphenyl)-1,3-diaminobenzene (PDA), Perylene
 and Perylene derivatives, phenyl-substituted cyclopentadiene derivatives,
 12-phthaloperinone derivatives (PP), squarilium dye (Sq),

- 1 1,1,4,4-tetraphenyl-1,3-butadiene (TPBD), sexithiophene (6T),
poly(2,4-bis(cholestanoxyl)-1,4-phenylene-vinylene (BCHA-PPV),
Polythiophenes, quinacridones (QA) (see T. Wakimoto et al., International
Symposium on Inorganic and Organic Electroluminescence, 1994,
5 Hamamatsu, 77), and substituted quinacridones (MQA), Rubrene, DCJT
(see for example: C. Tang, SID Conference San Diego; Proceedings, 1996,
181), conjugated and non-conjugated polymers, for example PPV and PPV
derivatives (soluble precursor), MEH-PPV
(poly(2-methoxyl,5-(2'-ethyl-hexoxy)-1,4-phenylene-vinylene), dialkoxy and
10 dialkyl PPV derivatives, segmented PPVs (see for example: E. Staring in
International Symposium on Inorganic and Organic Electroluminescence,
1994, Hamamatsu, 48, and T. Oshino et al. in Sumitomo Chemicals, 1995
monthly report).
- 15 **Hole transport layers and Hole injection layers:**
The following materials are suited as hole injection layers and hole
transport layers. Materials containing aromatic amino groups, like TDP,
NPB (see C. Tang, SID Meeting San Diego, 1996, and C. Adachi et al.
Applied Physics Letters, Vol. 66, p. 2679, 1995), TPA, NIPC, TPM, DEH (for
20 the abbreviations see for example: P. Borsenberger and D.S. Weiss,
Organic Photoreceptors for Imaging Systems, Marcel Dekker, 1993). These
aromatic groups can also be incorporated polymers, starburst (for
example: TCTA, m-MTDATA, see Y. Kuwabara et al., Advanced Materials,
6, p. 677, 1994, Y. Shirota et al., Applied Physics Letters, Vol. 65, p. 807,
25 1994) and spiro compounds. Further examples are: Cu(II) phthalocyanine
(CuPc), NPB
(N,N'-diphenyl-N,N'-bis-(4-phenylphenyl)-1,1'-biphenyl-4,4'-diamine) distyryl
arylene derivatives (DSA), naphthalene, naphthostyrylamine derivatives
(e.g. NSD), Quinacridone (QA; also suited as dopant),
30 poly(3-methylthiophene) family (P3MT), Perylene and Perylene derivatives,
polythiophene (PT), 3,4,9,10-perylenetetracarboxylic dianhydride (PTCDA)
(also suited as isolator), tetraphenyldiaminodiphenyl (TPD-1, TPD-2, or
TAD), PPV and some PPV derivatives,

1 poly(2-methoxy,5-(2'-ethyl-hexoxy)-1,4-phenylene-vinylene (MEH-PPV),
poly(9-vinylcarbazole) (PVK), discotic liquid crystal materials (HPT).

There are many other organic materials known as being good light
5 emitters, and many more will be discovered. These materials can be used
as well for making light emitting structures according to the present
invention. Examples of such materials are given in the publications cited in
the introductory portion of the present description. The contents of these
publications is herewith incorporated by means of reference.

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Additionally, blend (i.e. guest host) systems containing active groups in a
polymeric binder are also possible. The concepts employed in the design
of organic materials for OLED applications are to a large extent derived
from the extensive existing experience in organic photoreceptors. A brief
15 overview of some organic materials used in the fabrication of organic
photoreceptors is found in the above mentioned publication of P.
Brosenberger and D.S. Weiss, and in Teltech, Technology Dossier Service,
Organic Electroluminescence (1995), as well as in the primary literatur.

20 OLEDs have been demonstrated using polymeric, oligomeric and small
organic molecules. The devices formed from each type of molecules are
similar in function, although the deposition of the layers varies widely. The
present invention is equally valid in all forms described above for
polymeric and oligomeric organic light emitting devices.

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Small Molecule devices are routinely made by vacuum evaporation. This is
extremely compatible with PEMBD of GaN. Evaporation can be performed
in a Bell jar type chamber with independently controlled resistive and
electron-beam heating of sources. It can also be performed in a Molecular
30 Beam Deposition System incorporating multiple effusion cells and
electron-beam evaporators. In each case, GaN deposition can occur in the
same chamber, a vacuum connected chamber, or even a separate chamber
if some atmospheric contamination is tolerable.

1 Oligomeric and Polymeric organics can also be deposited by evaporation
of their monomeric components with later polymerization via heating or
plasma excitation at the substrate. It is therefore possible to alloy these by
co-evaporation also, and they are fully compatible with monomeric
5 compounds.

In general, polymer containing devices (single layer, multilayer, polymer
blend systems, etc.) are made by dissolving the polymer in a solvent and
spreading it over the substrate either by spin coating or the doctor blade
10 technique. After coating the substrate, the solvent is removed by heating or
otherwise. This method allows the fabrication of well defined multilayer
structures, provided that the respective solvents for each subsequent layer
do not dissolve previously deposited layers. Additionally, hybrid devices
containing both polymeric and evaporated small organic molecules are
15 possible. In this case, the polymer film is generally deposited first, since
evaporated small molecule layers cannot withstand much processing.
More interesting is the possibility of making a polymer/inorganic transport
layer on top of which monomeric layers are evaporated, possibly also
incorporating alloys. If the polymer is handled in an inert atmosphere prior
20 to introduction to vacuum, sufficient cleanliness for device fabrication is
maintained. In any case, the chemical inertness of GaN and other n-d WBS
makes it highly tolerant of polymer OLED processing.

To summarize, all inventions here are fully compatible to polymeric,
25 oligomeric, and small molecule OLED designs, or any hybrid design
thereof.

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CLAIMS

1. Organic light emitting device having
 - a) a substrate (60; 70; 80; 90; 100; 110; 120; 130),
 - 5 b) an anode electrode (64; 71; 81; 91; 101; 111; 123; 136),
 - c) a cathode (61; 75; 84; 94; 104; 113; 121; 133), and
 - d) an organic region (65; 76; 85; 95; 105; 112; 122; 135) in which electroluminescence takes place if a voltage is applied between said anode and cathode,
 - 10 said device being characterized in that said cathode comprises Gallium Nitride (GaN).
2. The light emitting device of claim 1, wherein the sequence of layers is: substrate/cathode/organic region/anode.
- 15 3. The light emitting device of claim 2, wherein light generated by said electroluminescence is either emitted from said organic region through said anode, or from said organic region through said cathode and substrate, or both.
- 20 4. The light emitting device of claim 1, wherein the sequence of layers is: substrate/anode/organic region/cathode.
5. The light emitting device of claim 4, wherein light generated by said
25 electroluminescence is either emitted from said organic region through said cathode, or from said organic region through said anode and substrate, or both.
6. The light emitting device of claim 1, wherein said organic region
30 comprises a single organic layer or a stack of organic layers.

- 1 7. The light emitting device of claim 1, wherein said Gallium Nitride is
alloyed with Aluminum, Indium, Arsenic, Phosphorous, Antimony, or
some combination of any two or more.
- 5 8. The light emitting device of claim 1, wherein said cathode (94; 104)
comprises an interlayer (94.1; 104.2).
9. The light emitting device of claim 8, wherein said interlayer is either in
direct contact with said organic region, or included in said cathode
10 near to the interface between said organic region and said cathode.
10. The light emitting device of claim 8, wherein said interlayer (94.1;
104.2) comprises a metal.
- 15 11. The light emitting device of claim 1, wherein said organic region (65;
76; 85; 95; 105) comprises an electron transport layer (62; 74; 83; 93;
103) being arranged such that said cathode (61; 75; 84; 94; 104) is in
direct contact with said electron transport layer.
- 20 12. The light emitting device of claim 1, wherein said substrate (70; 80; 90;
100; 130) is transparent or semitransparent.
13. The light emitting device of claim 1, wherein said substrate consists of
Silicon, glass or plastic.
- 25 14. The light emitting device of claim 1, wherein said substrate is flexible.
15. The light emitting device of claim 1, wherein said substrate is a Silicon
substrate (110; 120) comprising integrated circuits.
- 30 16. The light emitting device of claim 1, wherein said Gallium Nitride is
either polycrystalline or amorphous.

- 1 17. The light emitting device of claim 2, wherein said cathode comprises
an Indium-Tin-Oxide (ITO) layer separating said Gallium Nitride from
said substrate.
- 5 18. The light emitting device of claim 1, wherein said organic region
comprises either
- a stack of more than one organic emission layers (EL), or
 - an organic compound doped with one or more impurities, organic
or inorganic, chosen to dominate and enhance the
10 electroluminescence, or
 - a stack of more than one organic emission layer, some of which
may be doped to dominate or enhance the electroluminescence of
that particular organic emission layers, or
 - a stack of more than one organic layer, in which the role of one or
15 more of said organic layers is to electrically confine one or more
carrier types to improve the emission of an adjacent organic
layer.
- 20 19. Organic light emitting array or display comprising more than one light
emitting device pursuant to any of the preceding claims.
- 25 20. The organic light emitting array or display of claim 19, wherein said
substrate is a Silicon substrate comprising devices and/or circuits
and/or electrical connections.
- 30 21. The organic light emitting array or display of claim 20, wherein said
devices and/or circuits and/or electrical connections are designed for
driving and controlling at least one of said light emitting devices.
22. The organic light emitting array or display of claim 20, comprising
color filters (132) providing for the emission of light at different
wavelengths, or color conversion layers (132), providing for the
conversion of the organic light emitting device's emissive wavelength.

- 1 23. The organic light emitting array or display of claim 20, wherein said
light emitting devices are deposited cathode first onto said Silicon
substrate, and wherein
- said cathode comprising Gallium Nitride injects electrons
 - 5 efficiently into the organic region of said light emitting devices,
and
 - the anode of said light emitting devices is transparent or
semitransparent,
- 10 arranged such that light emitted by said light emitting devices is
emitted into the half space above the Silicon substrate plane.
- 15 24. The organic light emitting array or display of claim 20, wherein said
light emitting devices are deposited anode first onto said Silicon
substrate, and wherein said cathode comprising Gallium Nitride is
transparent or semitransparent such that light emitted by said light
emitting devices is emitted into the half space above the Silicon
substrate plane.
- 20 25. The organic light emitting array or display of claim 21, wherein said
light emitting devices are formed such that light is emitted from said
organic region through said cathode and substrate into the half space
below said substrate plane.
- 25 26. The organic light emitting array or display of claim 19, wherein the
substrate and the entire array or display are flexible.
- 30 27. Method for making organic light emitting devices having a substrate,
an anode electrode, a cathode, and an organic region in which
electroluminescence takes place if a voltage is applied between said
anode and cathode, comprising the steps of:
- a) forming said cathode such that it comprises Gallium Nitride (GaN).
28. The method of claim 27, whereby said cathode is formed using

- 1 • an electron cyclotron resonance or radio-frequency (RF) plasma,
 or
- metalorganic chemical vapor deposition, or
- magnetron sputtering, or
- 5 • laser ablation, or
- a plasma enhanced molecular beam deposition.

29. The method of claim 27, whereby said cathode is formed at low
temperature below 150 degree centigrade, and preferably at a
10 temperature in the range of the room temperature.

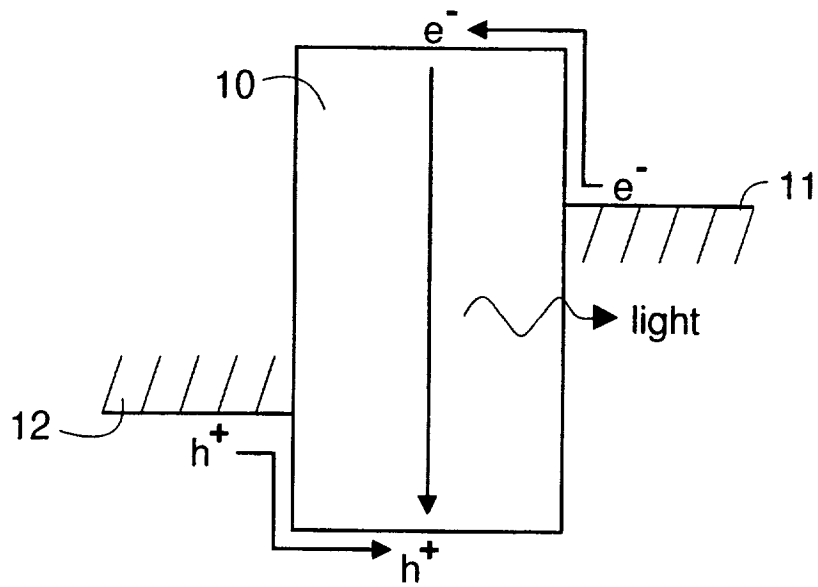
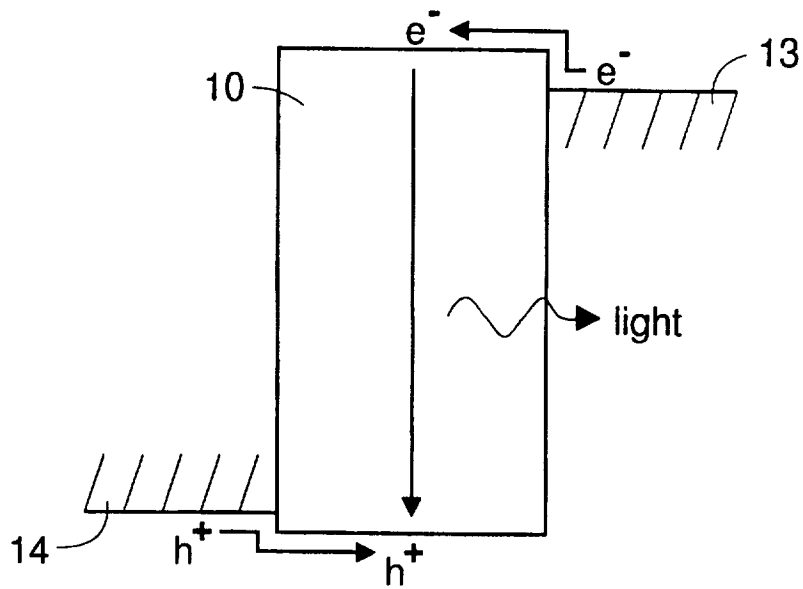
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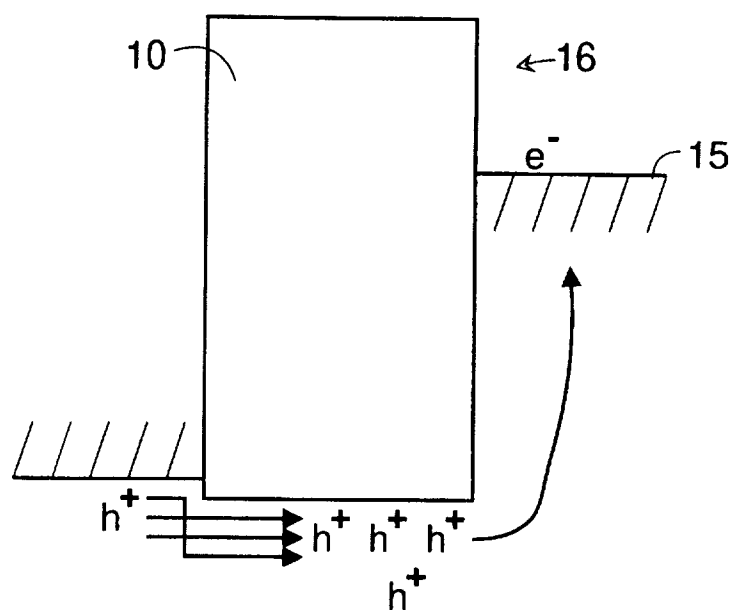
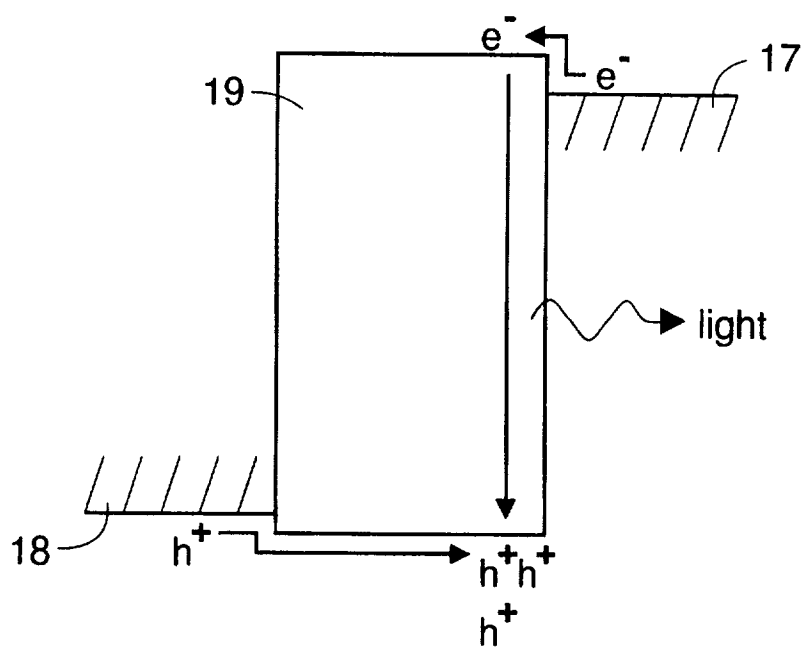
25

30

1/12

FIG. 1A
(Prior Art)FIG. 1B
(Prior Art)

2/12

FIG. 2A
(Prior Art)FIG. 2B
(Prior Art)

3/12

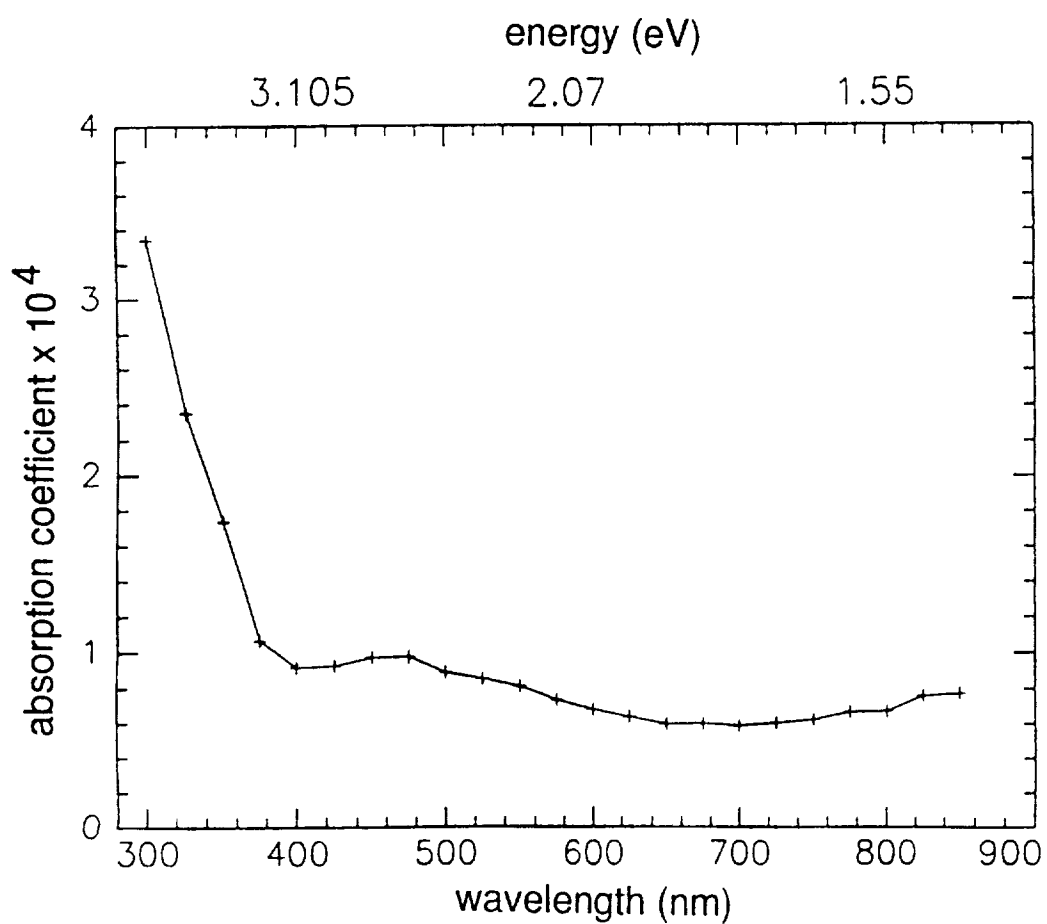
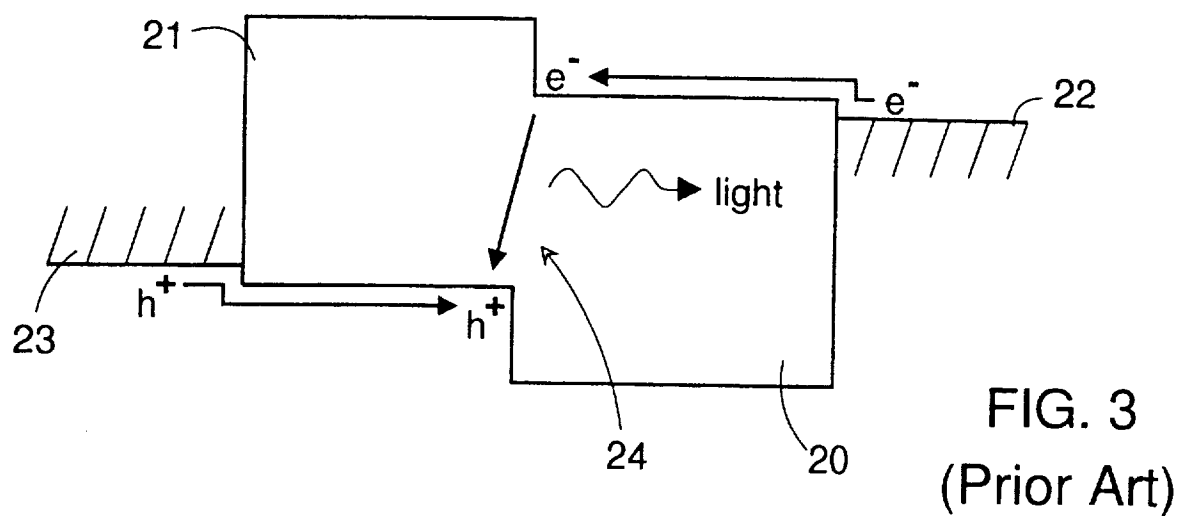


FIG. 4

4/12

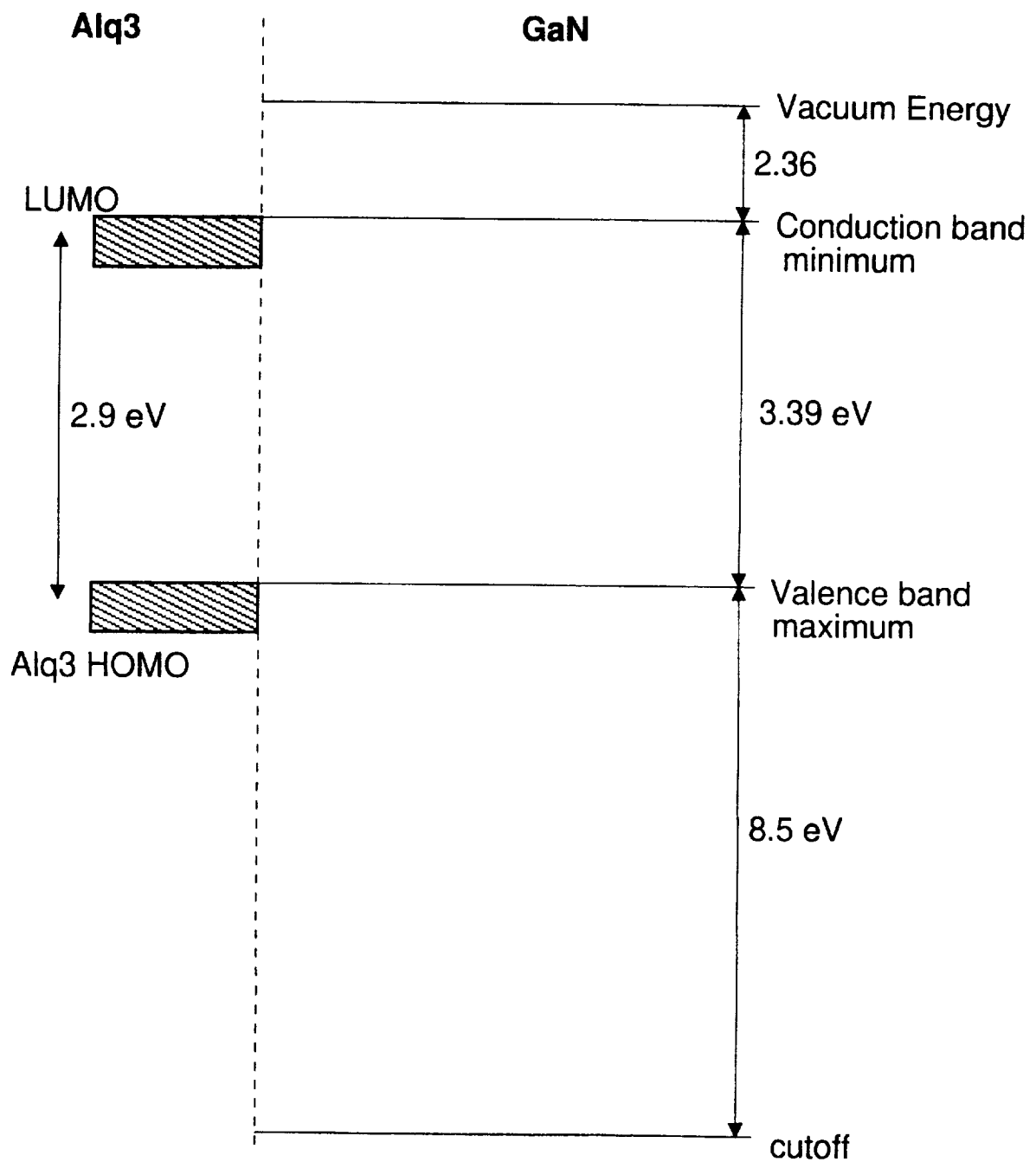
Energy level diagram for
GaN and Alq3

FIG. 5

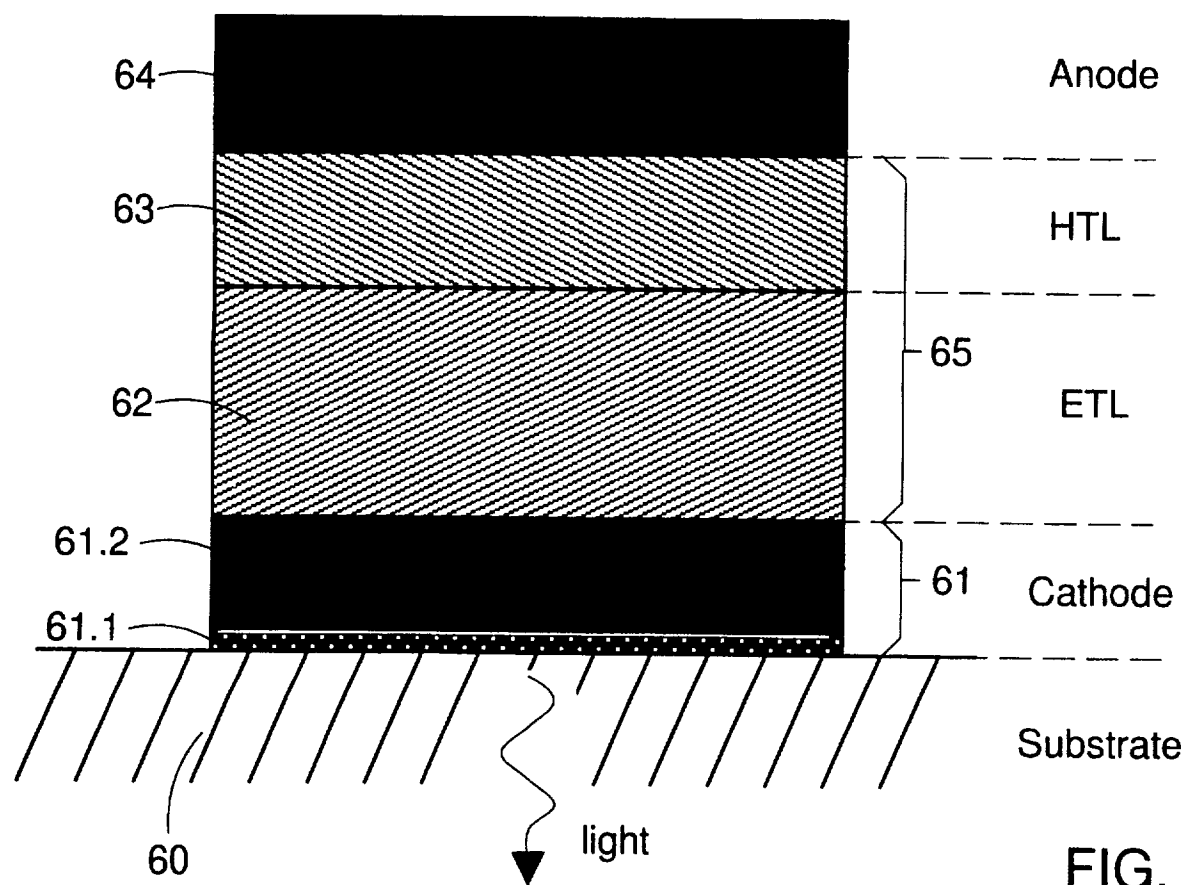


FIG. 6

6/12

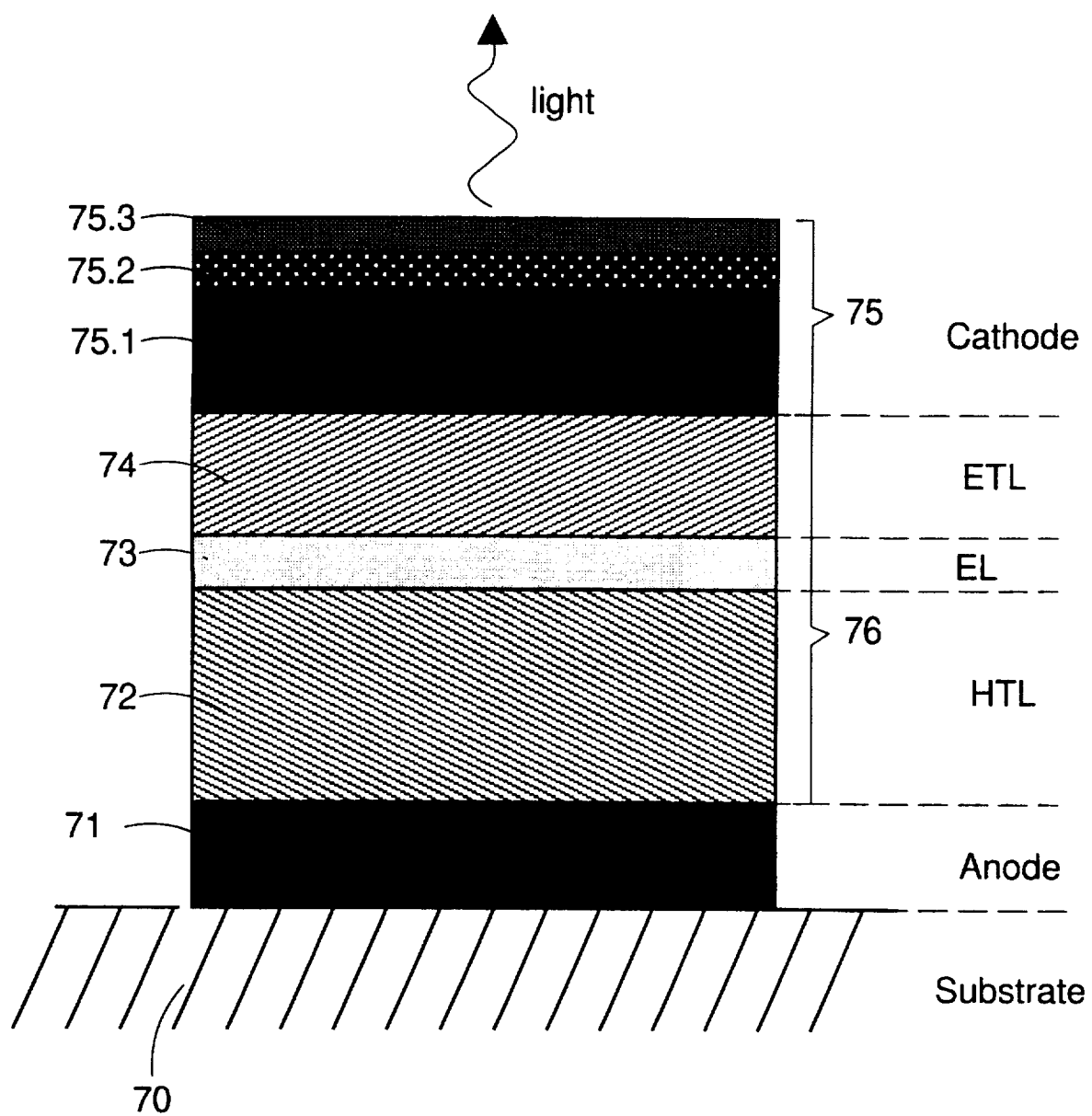


FIG. 7

7/12

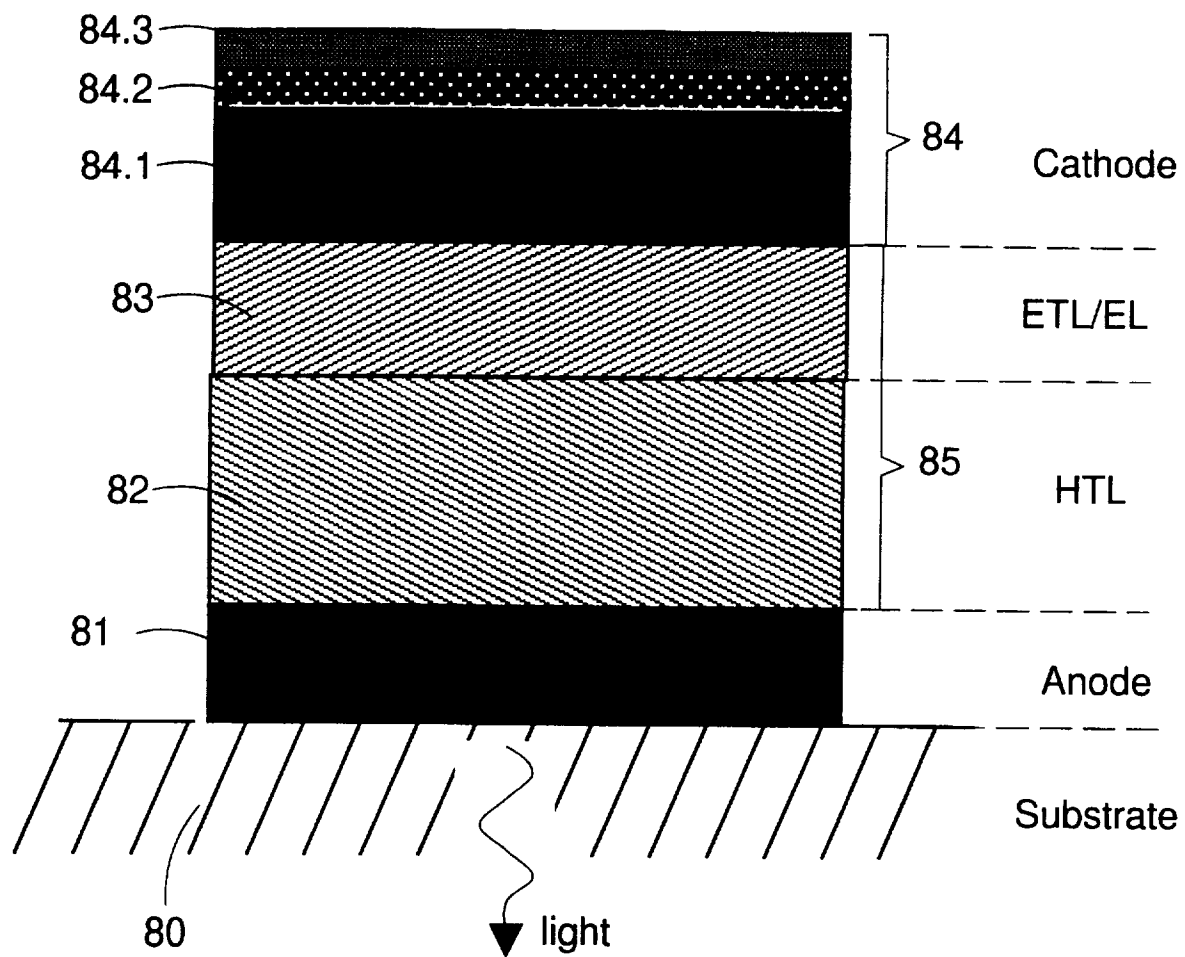


FIG. 8

8/12

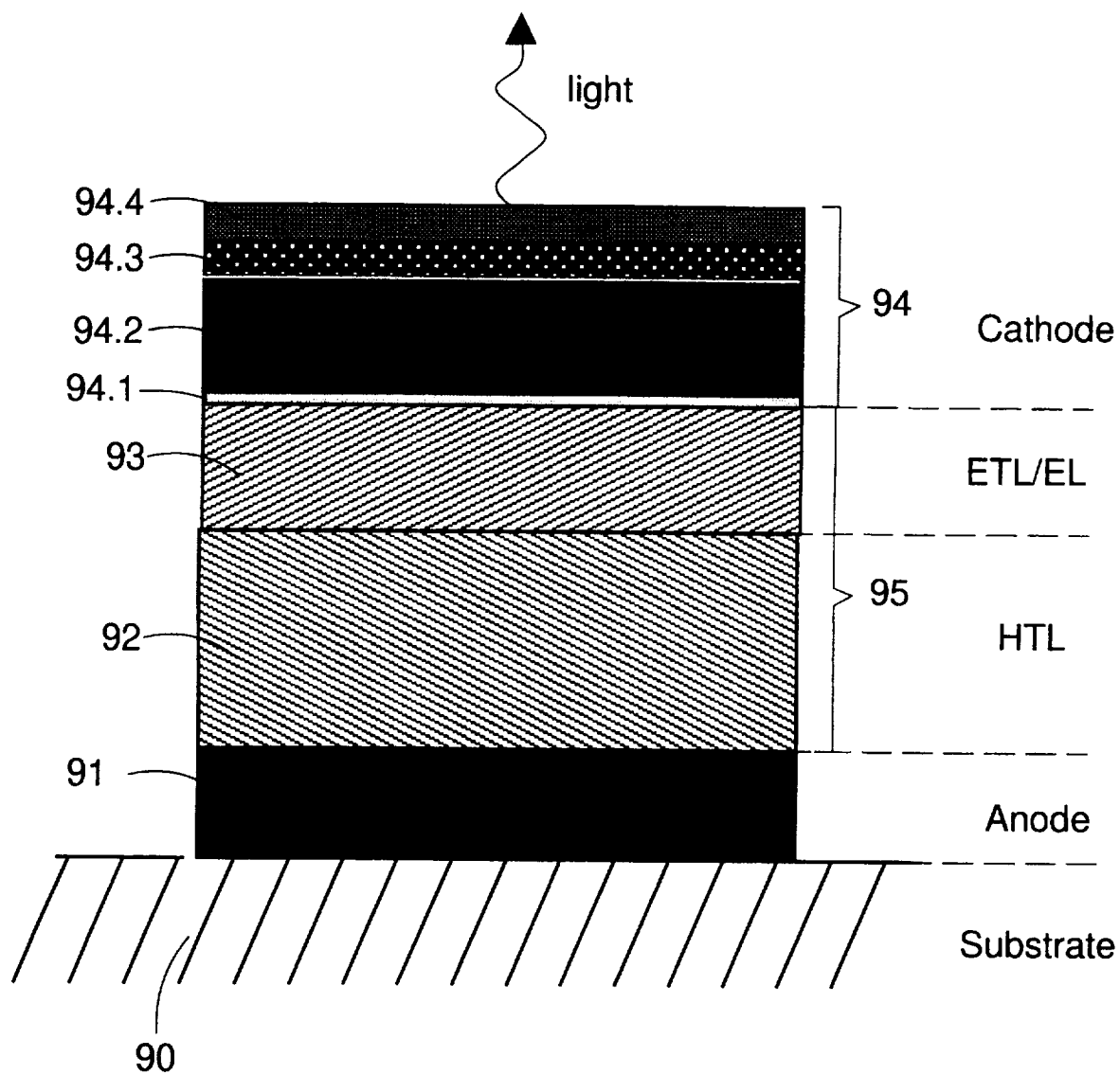


FIG. 9

9/12

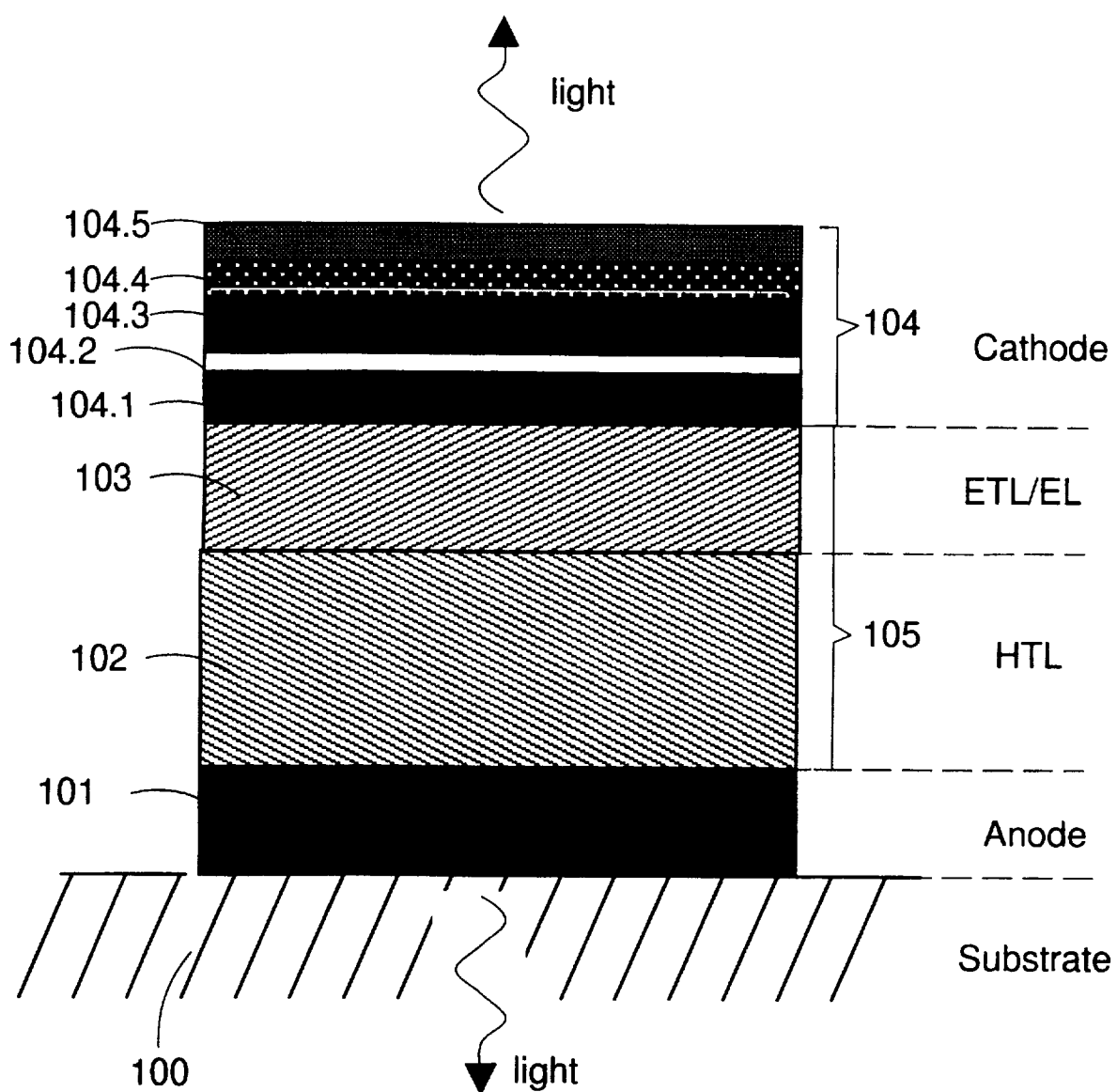


FIG. 10

10/12

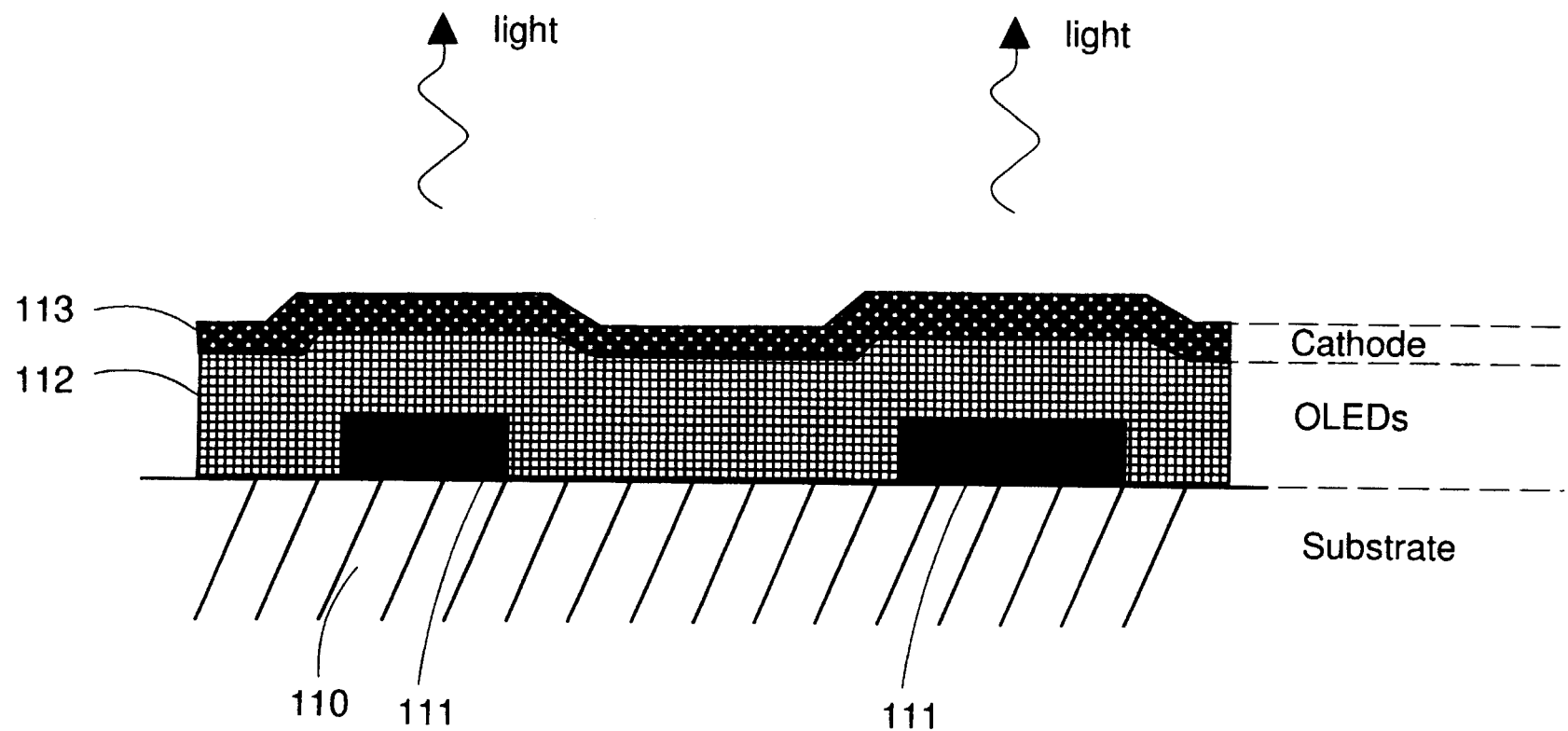


FIG. 11

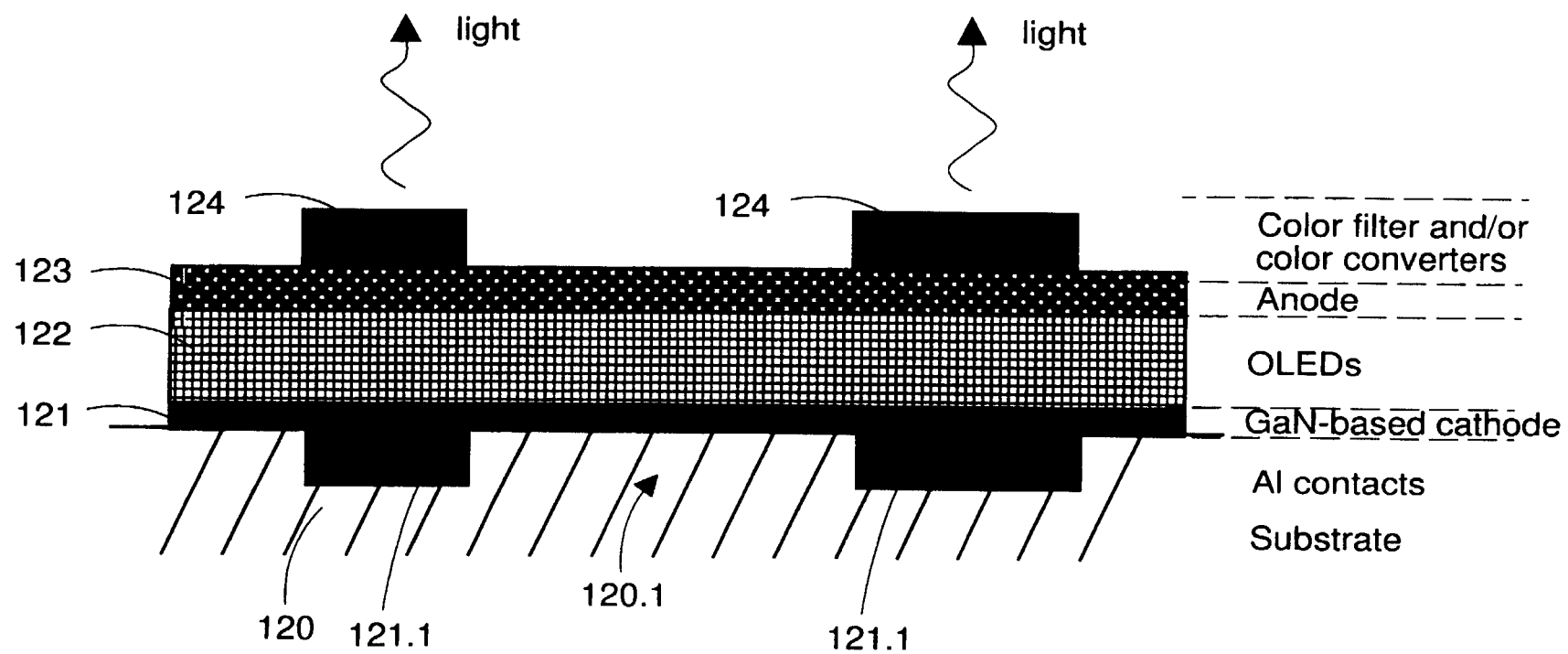


FIG. 12

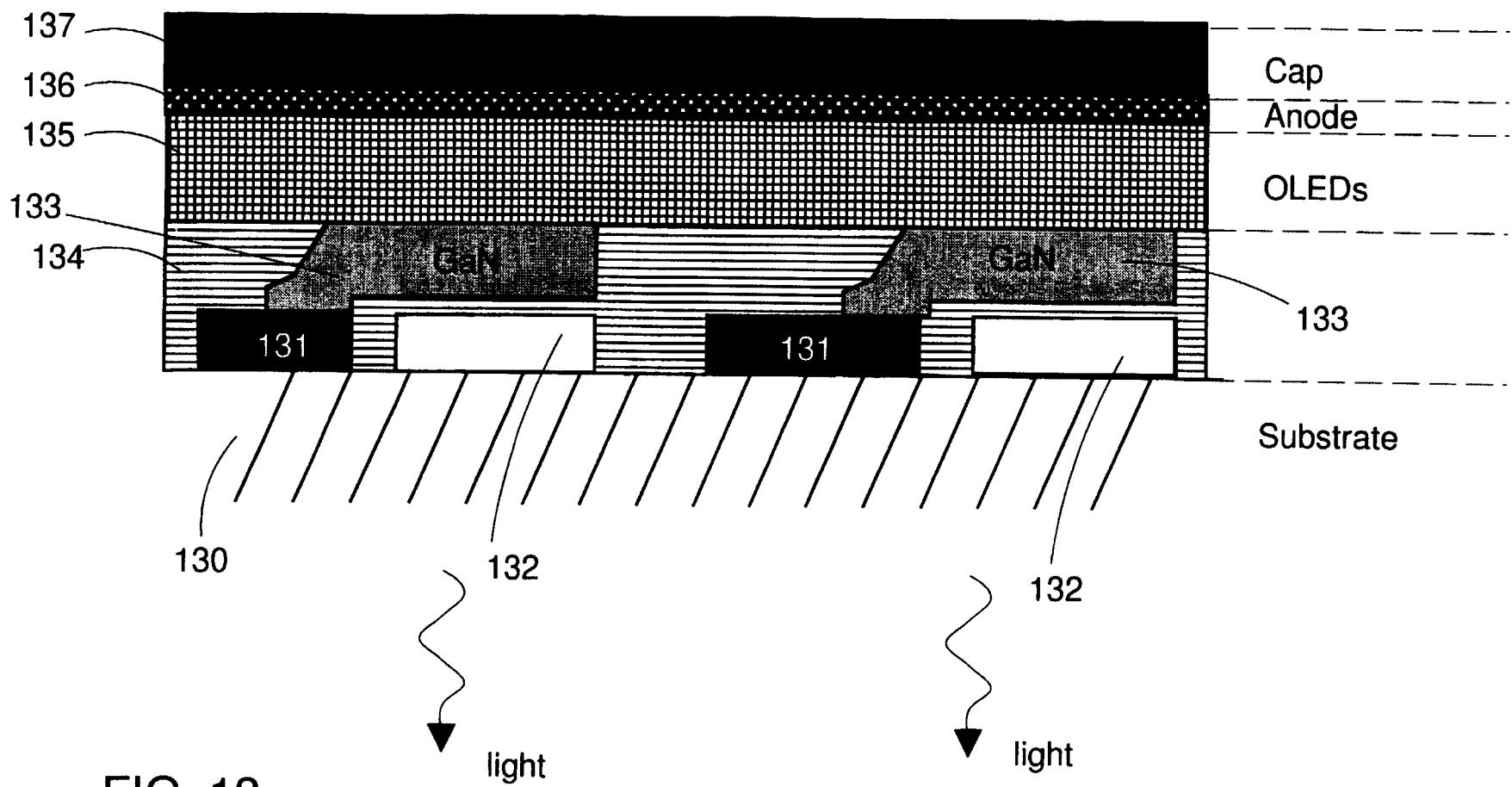


FIG. 13

INTERNATIONAL SEARCH REPORT

 Inter nal Application No
 PCT/IB 96/00780

 A. CLASSIFICATION OF SUBJECT MATTER
 IPC 6 H01L51/20 H01L33/00

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)
 IPC 6 H01L H05B

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)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	JOURNAL OF VACUUM SCIENCE AND TECHNOLOGY: PART A, vol. 11, no. 4, PART 01, 1 July 1993, pages 1422-1425, XP000403745 SATO H ET AL: "TRANSPARENT AND CONDUCTIVE GAN THIN FILMS PREPARED BY AN ELECTRON CYCLOTRON RESONANCE PLASMA METALORGANIC CHEMICAL VAPOR DEPOSITION METHOD" cited in the application see the whole document ---	1,27-29
A	EP,A,0 448 268 (TOKYO SHIBAURA ELECTRIC CO) 25 September 1991 see page 3, line 41 - line 47 -----	1

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

☒ Patent family members are listed in annex.

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Date of the actual completion of the international search

12 February 1997

Date of mailing of the international search report

27.02.97

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De Laere, A

INTERNATIONAL SEARCH REPORT

Information on patent family members

Internal Application No.

PCT/IB 96/00780

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
EP-A-0448268	25-09-91	JP-A- 3262170	21-11-91
		US-A- 5105233	14-04-92
