

LIGHT EXTRACTION FILM WITH NANOPARTICLE COATINGS

BACKGROUND

Organic Light Emitting Diodes (OLEDs) are the basis for a new display and lighting technology, providing a good match for high resolution or high pixel count high definition display applications, and for efficient, broad area, flexible lighting applications. OLED devices include a thin film of electroluminescent organic material sandwiched between a cathode and an anode, with one or both of these electrodes being a transparent conductor. When a voltage is applied across the device, electrons and holes are injected from their respective electrodes and recombine in the electroluminescent organic material through the intermediate formation of emissive excitons.

In OLED devices, over 70% of the generated light is typically lost due to processes within the device structure. The trapping of light at the interfaces between the higher index organic and Indium Tin Oxide (ITO) layers and the lower index substrate layers is the major cause of this poor extraction efficiency. Only a relatively small amount of the emitted light emerges through the transparent electrode as “useful” light. The majority of the light undergoes internal reflections, which result in its being emitted from the edge of the device or trapped within the device and eventually being lost to absorption within the device after making repeated passes.

Efforts have been made to improve the internal quantum efficiency (number of photons generated per electron injected) of OLEDs by means such as modifying the charge injection or transport layers, using fluorescent dyes or phosphorescent materials, or by using multilayer structures (see, for example, K.Meerholz, Adv.Funct.Materials v.11, no.4, p251 (2001)). Light extraction efficiency (number of photons emerging from the structure vs. the number generated internally) can be influenced by factors external to the emission layers themselves.

A bottom emitting OLED may be thought of as consisting of a core containing high index of refraction layers (organic layers for light generation, carrier transport, injection or blocking, and, typically, a transparent conductive oxide layer) and a low index of refraction substrate material (typically glass, but could be a polymer film). Therefore light that is generated within the core may encounter two high index to low index interfaces where it might undergo internal reflection. Light unable to escape the core as a

result of encounter at the first interface is confined to a waveguide mode, while light passing through that interface but unable to escape from the substrate as a result of reflection at the substrate-to-air interface is confined to a substrate mode. Similar optical losses occur due to interfaces in top emitting OLEDs.

5 Various solutions have been proposed to affect light reaching the substrate-to-air interface by disturbing that interface (e.g., microlenses or roughened surfaces). Others have introduced scattering elements into the substrate or into an adhesive (see Published PCT Application No. WO2002037580A1 (Chou)), thereby interrupting the substrate modes to redirect that light out of the device. There have even been some preliminary
10 attempts to disturb the core-to-substrate interface by introducing scattering or diffractive elements at this interface. Detailed analysis has shown that scattering or diffracting structures will be most effective in extraction light when located at this interface (M.Fujita, et al.; Jpn.J.Appl.Phys. 44 (6A), pp.3669-77 (2005)). Scattering efficiency is maximized when the index contrast between the scattering or diffractive elements and the
15 backfill material is large and when the length scale of the index contrast variations is comparable to the wavelength of the light (see, for example, F.J.P.Schuurmans, et al.; Science 284 (5411), pp.141-143 (1999)).

 Fabrication of defect-free OLED devices in contact with this light extracting layer will require a smooth planar surface, so planarity of the top surface of a light extraction
20 film is important. There has been, however, some work on corrugating the electrode structure in order to couple light out of the OLED (M.Fujita, et al.; Jpn.J.Appl.Phys. 44 (6A), pp.3669-77 (2005)); the resultant effects on the electric fields in the device are expected to have deleterious effects. So great care must be taken to not adversely affect the electrical operation of the device while disturbing this interface. Practical solutions to
25 balancing these conflicting issues have not yet been proposed.

 Similar problems in external efficiency exist with inorganic light-emitting diodes (LEDs), where the very high refractive indices of the active materials can severely limit the extraction of internally generated light. In these cases, there have been some attempts to utilize photonic crystal (PC) materials to improve the extraction efficiency (S.Fan, Phys.Rev.Letters v.78, no.17, p.3294 (1997); H.Ichikawa, Appl.Phys.Letters V.84, p.457
30 (2004)). Similar reports on the use of PCs in connection with OLED efficiency improvement have begun to appear (M.Fujita, Appl.Phys.Letters v.85, p.5769 (2004);

Y.Lee, Appl.Phys.Letters v.82, p.3779 (2003)), but previously reported results have involved time-consuming and costly procedures which do not lend themselves incorporation into existing OLED fabrication processes.

Accordingly, a need exists for a product which can enhance light extraction from OLED devices in a form which is compatible with fabrication processes for these devices.

SUMMARY

A multifunctional optical film for enhancing light extraction, consistent with the present invention, includes a flexible substrate, a structured layer, and a backfill layer.

The structured layer of extraction elements has a first index of refraction, and a substantial portion of the extraction elements are in optical communication with a light emitting region of a self-emissive light source when the optical film is located against the self-emissive light source. The extraction elements include nanoparticles of different sizes. The backfill layer has a material having a second index of refraction different from the first index of refraction, and the backfill layer forms a planarizing layer over the extraction elements.

A method of making a multifunctional optical film for enhancing light extraction, consistent with the present invention, includes coating a layer of a material having a first index of refraction onto a flexible substrate. Nanostructured features of different sizes are imparted into the organic material to create a nanostructured surface. The organic material having the nanostructured features is cured. A backfill layer is then applied to the nanostructured surface to form a planarizing layer on the nanostructured surface. The backfill layer comprises a material having a second index of refraction different from the first index of refraction. Alternatively, a thin layer of nanoparticles may be distributed on the surface of the film and then overcoated with an essentially planarizing material of a different index.

BRIEF DESCRIPTION OF THE DRAWINGS

The accompanying drawings are incorporated in and constitute a part of this specification and, together with the description, explain the advantages and principles of the invention. In the drawings,

FIG. 1 is a diagram of a bottom emitting OLED display device with a light extraction film;

FIG. 2 is a diagram of a top emitting OLED display device with a light extraction film;

5 FIG. 3 is a diagram illustrating spatially modulated OLEDs for a solid state lighting element;

FIG. 4 is a diagram of an OLED backlight unit with a light extraction film;

FIG. 5 is a diagram illustrating OLEDs used as an LCD backlight unit;

10 FIGS. 6-9 are diagrams depicting possible spatial configurations of extraction elements; and

FIGS. 10-14 are diagrams depicting possible surface configurations of extraction elements.

DETAILED DESCRIPTION

15 Embodiments include methods to form light-extracting nanostructures, or other nanostructures, in a polymer replication process, a direct deposition of nanoparticles, or other processes to make a light extraction film for OLED devices. The multifunctional film product can, in addition to enhancing light extraction, serve additional functions such as a substrate, encapsulant, barrier layer, filter, polarizer, or color converter and may be
20 employed either during or after manufacture of an OLED device. The film construction is based upon photonic crystal structures, or other nanostructures, for improved efficiency of light extraction from the devices by modifying the interface between high and low index layers within the device.

25 Elements of the invention include the provision of structures of dimensions comparable to or less than the wavelength of the light to be controlled, the provision of a material with contrasting index of refraction to fill in the areas surrounding the structures and also to planarize the structure in order to present an essentially smooth surface to come in contact with the OLED structure, and the location of this index-contrasting nanostructured layer within a small enough distance from the light-emitting region to be
30 effective in extracting the light that would otherwise be trapped in that region.

Light incident from a high index material onto an interface with a lower index medium will undergo total internal reflection (TIR) for all incidence angles greater than

the critical angle θ_C , defined by $\theta_C = \sin^{-1}(n_2/n_1)$, where n_1 and n_2 are the refractive indices of the high- and low index regions, respectively. The electromagnetic field associated with this light reflected by TIR extends into the lower-index region in an evanescent standing wave, but the strength of this field diminishes exponentially with distance from the interface. Absorbing or scattering entities located within this evanescent zone, typically about one wavelength thick, can disrupt the TIR and cause the light to pass through the interface. Therefore, it is preferable that the nanostructured index contrast layer be located within the evanescent zone if it is to be most effective in causing extraction of the light from the emission region by scattering or diffraction. Alternatively, the nanostructured index contrast layer need only be in optical communication with a light emitting region of the self-emissive light source when the optical film is located against the self-emissive light source. The term "optical communication" means that a significant or substantial portion of the generated optical field from the light source is capable of reaching the scattering particles or nanostructure.

Replication master tools can be fabricated with regular or random structures of the required average periodicity for light extraction, 200 nanometers (nm)–2000nm, over increasingly larger areas. Combining this tooling capability with microreplication processes such as continuous cast and cure (3C) enable the formation of the photonic crystal structures, or other nanostructures, on the surface of a film substrate. Examples of a 3C process are described in the following patents, all of which are incorporated herein by reference as if fully set forth: U.S. Patent Nos. 4,374,077; 4,576,850; 5,175,030; 5,271,968; 5,558,740; and 5,995,690.

The terms "nanostructure" or "nanostructures" refers to structures having at least one dimension (e.g., height, length, width, or diameter) of less than 2 microns and more preferably less than one micron. Nanostructure includes, but is not necessarily limited to, particles and engineered features. The particles and engineered features can have, for example, a regular or irregular shape. Such particles are also referred to as nanoparticles.

The term "nanostructured" refers to a material or layer having nanostructures.

The term "photonic crystal structures" refers to periodic or quasi-periodic optical nanostructures interspersed with a material of sufficiently different index of refraction that will enable the structure to produce gaps in the spectrum of allowed electromagnetic modes in the material.

The term "index" refers to index of refraction.

The term "backfill" refers to the material incorporated into a structure, and of a different index from the structure, to fill in voids in the structure and planarize the structure.

5 The term "extraction elements" refers to any type and arrangement of nanostructures enhancing light extraction from self-emissive light sources. The extraction elements are preferably not contained within a volume distribution.

Bottom Emitting OLED Display Device

10 FIG. 1 illustrates a structure of bottom emitting OLED device 100 having a light extraction film. A bottom emitting OLED device is defined as an OLED device emitting light through the substrate. Table 1 describes the exemplary elements of device 100 and the arrangement of those elements, as identified by the reference numbers provided in FIG. 1. Each layer of device 100 can be coated on or otherwise applied to the underlying
15 layer.

Table 1 - Bottom Emitting OLED Device with Light Extraction Film	
Ref. No.	Type of Element
102	electrode 1
104	organic layers
106	electrode 2
108	high index structure
110	low index structure
112	optional barrier layer
114	substrate
115	optional functional layers
116	light extraction film

The substrate 114 is composed of a material, substantially transparent (transmissive) to the desired emitted wavelengths, that provides sufficient mechanical support and thermal stability for the device. Substrate 114 preferably comprises a flexible material. Examples of substrate materials include the following: glass; flexible glass; polyethylene terephthalate ("PET"); polyethylene naphthalate ("PEN"); or other translucent or transparent materials. Substrate 114 can optionally also function as a barrier layer. Also, substrate 114 can optionally contain dyes or particles, and it can be tented or include prismatic structures.

The optional barrier layer 112 effectively blocks or helps prevent permeation of oxygen and water to the layers of the device, particularly the organic layers. Examples of barrier layers are described in U.S. Patent Application Publication Nos. 2006/0063015 (describing boron oxide layers with inorganic barrier layers) and 2007/0020451 (describing diamond-like glass (DLG) and diamond-like carbon (DLC)), both of which are incorporated herein by reference as if fully set forth.

The electrodes 102 and 106 can be implemented with, for example, transparent conductive oxide (TCO) such as indium tin oxide (ITO) or metals with the appropriate work function to make injection of charge carriers such as calcium, aluminum, gold, or silver.

The organic layers 104 can be implemented with any organic electroluminescent material such as a light-emitting polymer, an example of which is described in U.S. Patent No. 6,605,483, which is incorporated herein by reference as if fully set forth. Other examples of suitable light emitting materials include evaporated small molecule materials,

light-emitting dendrimers, molecularly doped polymers, and light-emitting electrochemical cells.

The light extraction film 116 in this embodiment is composed of substrate 114, optional barrier layer 112, low index structure 110, and high index structure 108. The high index structure uses a backfill medium to effectively provide a planarizing layer over the low index structure in order to make the light extraction film sufficiently planar to allow OLED fabrication. The backfill layer can alternatively have other optical properties. Also, the backfill layer material can function as a barrier to moisture and oxygen or provide electrical conduction, possibly in addition to having barrier properties, depending upon the type of material used. The backfill layer can alternatively be implemented with an optically clear adhesive, in which case the extraction film can be applied to top emitting OLED device, for example. A stabilization layer can optionally be coated on the device before applying the backfill layer.

The low index structure 110 has a material with an index substantially matched to the underlying layer, typically the substrate. The low index structure 110 is composed of a nanostructured layer, which can have a periodic, quasi-periodic, or random distribution or pattern of optical nanostructures, including photonic crystal structures. It can include discrete nanoparticles. The nanoparticles can be composed of organic materials or other materials, and they can have any particle shape. The nanoparticles can alternatively be implemented with porous particles. The distribution of nanostructures can also have varying pitches and feature size. At least a portion of the extraction elements or nanostructures are preferably in contact with the flexible substrate, and the extraction elements may have voids beneath them. The layer of nanoparticles can be implemented with nanoparticles in a monolayer, with a layer having agglomerations of nanoparticles, or in a multi-layer.

In some embodiments, the addition of small SiO₂ nanoparticles to suspensions of larger SiO₂ nanoparticles for low index structure 110 can significantly improve the uniformity of the larger nanoparticles in coatings made from the suspension. For example, low index structure 110 can include the additional of 5nm diameter SiO₂ nanoparticles in coatings made from suspensions of 440nm diameter SiO₂ nanoparticles. These small and large nanoparticles can be surface treated or non-treated. The large nanoparticles can comprises two or more different sizes of large nanoparticles. The large nanoparticles

preferably have diameters in the range of 60nm to 10 microns, or 100nm to 1 micron, or more preferably 100nm to 500nm. The small nanoparticles preferably have diameters in the range of 3nm to 50nm. The nanoparticles can comprise one or more of the following: metal oxide particles; organic polymer particles; metal particles; or composite particles.

5 Using a distance of the nanostructures on the order of the evanescent wave from the organic layers can result in coupling of the evanescent wave to the nanostructures for extraction of additional light from the device. This coupling preferably occurs when the light extraction film is adjacent to the light emitting region of the self-emissive light source. When the backfill layer has a lower index than the structured layer, then the
10 backfill layer preferably has a thickness substantially equal to the extraction elements. When the backfill layer has a higher index than the structured layer, then the backfill layer can be thicker than the extraction elements provided it can still interact with the evanescent wave. In either case, the structured layer and backfill layer are preferably in sufficient proximity to the light output surface in order to at least partially effect the
15 extraction of light from that surface.

 The nanostructured features in layer 110 can be fabricated using any printing techniques for replication of submicron features such as the following: imprinting; embossing; nanoimprinting; thermal- or photo-nanoimprint lithography; injection
20 molding; or nanotransfer printing. Another technique for fabricating the extraction elements is described in Example 18 in U.S. Patent No. 6,217,984, which is incorporated herein by reference as if fully set forth.

 The high index structure 108 is a high index material providing index contrast to the adjacent low index nanostructured layer and provides an effective planarization layer to it. The index of refraction mismatch between nanostructured layer 110 and backfill
25 medium 108 at the emission wavelength(s) is referred to as Δn , and a greater value of Δn generally provides better light extraction. The value of Δn is preferably greater than or equal to 0.3, 0.4, 0.5, or 1.0. Any index mismatch between the extraction elements and backfill medium will provide for light extraction; however, a greater mismatch tends to provide greater light extraction and is thus preferred. Examples of suitable materials for
30 backfill medium 108 include the following: high index inorganic materials; high index organic materials; a nanoparticle filled polymer material; silicon nitride; polymers filled with high index inorganic materials; and high index conjugated polymers. Examples of

high index polymers and monomers are described in C.Yang, et al., Chem.Mater. 7, 1276 (1995), and R.Burzynski, et al., Polymer 31, 627 (1990) and U.S. Patent No. 6,005,137, all of which are incorporated herein by reference as if fully set forth. Examples of polymers filled with high index inorganic materials are described in U.S. Patent No. 6,329,058, which is incorporated herein by reference as if fully set forth. The backfill layer can be applied to form the planarizing layer using, for example, one of the following methods: liquid coating; vapor coating; powder coating; or lamination.

Functionality can be added to the construction by depositing on it a transparent conductor such as ITO ($n \approx 1.9-2.1$) with high index, high transparency and low sheet resistivity, to serve as the anode for the OLED device. The ITO can even be used as the backfill for the structure, if the layer can fill the structures and form into a smooth layer without adverse effects on the optical or electrical properties. Alternatively, after backfilling and smoothing, alternating metallic and organic layers may be deposited to form a transparent conductive overlayer (on the backfill layer) in the manner as described in U.S. Patent Application Publication No. 2004/0033369, which is incorporated herein by reference as if fully set forth.

Additional flexibility in the functionality of the extractor pattern of the photonic crystal structures or nanostructures can be obtained through the use of photonic quasicrystal structures. These quasicrystal structures are designed using tiling rules; they have neither true periodicity nor translation symmetry but have a quasi-periodicity with long-range order and orientation symmetry, examples of which are described in the following reference, which is incorporated herein by reference as if fully set forth: B. Zhang et al., "Effects of the Artificial Ga-Nitride/Air Periodic Nanostructures on Current Injected GaN-Based Light Emitters," Phys.Stat.Sol.(c) 2(7), 2858-61 (2005). The photonic quasicrystal structures offer the possibility of a pseudogap for all propagation directions, and they exhibit unique light scattering behaviors. In particular, these patterns of quasiphotonic crystal structures can eliminate artifacts resulting from the regularity of conventional photonic crystal structures, and they can be used to tailor unique light emission profiles and possibly can eliminate undesirable chromatic effects when working with broadband OLED emitters. Photonic crystal structures are described in the following patents, all of which are incorporated herein by reference as if fully set forth: U.S. Patent Nos. 6,640,034; 6,901,194; 6,778,746; 6,888,994; 6,775,448; and 6,959,127.

Embodiments can involve the incorporation of the diffractive or scattering nanostructures into a film product which could be continuously produced, for example, on a web line having a polymer film or ultrabARRIER coated film substrate fed to a 3C replication process followed by deposition of a high index backfill medium. Alternate
5 ways to incorporate the diffractive or scattering nanoparticles into the film include solution coating a dispersion of particles. This film can be designed to be used directly as the substrate on which a bottom emitting OLED is fabricated, enabling the production of a film capable of many uses in addition to enhancing light extraction.

Additional functionality could be incorporated into the light extraction film
10 product by forming the extraction structures on an optional ultrabARRIER film, which provides excellent moisture and oxygen barrier properties. UltrabARRIER films include multilayer films made, for example, by vacuum deposition of two inorganic dielectric materials sequentially in a multitude of layers on a glass or other suitable substrate, or alternating layers of inorganic materials and organic polymers, as described in U.S. Patent
15 Nos. 5,440,446; 5,877,895; and 6,010,751, all of which are incorporated herein by reference as if fully set forth.

Materials may also be incorporated within the film to enhance light extraction through scattering or to filter, color shift, or polarize the light. Finally, surface coatings or structures, for example functional layers 115, can be applied to the air surface of the light
20 extraction film in order to further increase the functionality and possibly value of a light extraction film. Such surface coatings can have, for example, optical, mechanical, chemical, or electrical functions. Examples of such coatings or structures include those having the following functions or properties: antifog; antistatic; antiglare; antireflection; antiabrasion (scratch resistance); antismudge; hydrophobic; hydrophilic; adhesion
25 promotion; refractive elements; color filtering; ultraviolet (UV) filtering; spectral filtering; color shifting; color modification; polarization modification (linear or circular); light redirection; diffusion; or optical rotation. Other possible layers to be applied to the air surface include a barrier layer or a transparent electrically conductive material.

30 **Top Emitting OLED Display Device**

FIG. 2 illustrates a structure of top emitting OLED device 120 with a film substrate having a light extraction film. Table 2 describes the exemplary elements of the device 120

and the arrangement of those elements, as identified by the reference numbers provided in FIG. 2. Each layer of the device can be coated on or otherwise applied to the underlying layer. The configurations shown in FIGS. 1 and 2 are provided for illustrative purposes only, and other configurations of bottom emitting and top emitting OLED display devices are possible.

Table 2 - Top Emitting OLED Device with Light Extraction Film	
Ref. No.	Type of Element
121	optional functional layers
122	substrate 1
124	optional barrier layer
126	low index structure
128	high index structure
130	optical coupling layer
132	electrode 1
134	optional thin film encapsulant layer
136	organic layers
138	electrode 2
140	substrate 2
142	light extraction film

The light extraction film 142 in this embodiment is composed of substrate 122, optional barrier layer 124, low index structure 126, and high index structure 128. Low index structure 126 and high index structure 128 can be implemented with the exemplary materials and constructions described above. Layers 128 and 130 can optionally be implemented with a single layer. The substrates 122 and 140, optional barrier layer 124, electrodes 132 and 138, and organic layers 136 can be implemented with the exemplary materials identified above. Substrate 140 can also be optionally implemented with an opaque material such as a metal foil.

Optional thin film encapsulant 134 can be implemented with, for example, any suitable material for protecting the organic layers from moisture and oxygen. Examples of encapsulants for OLED devices are described in U.S. Patent No. 5,952,778 and U.S. Patent Application Serial No. 11/424997, filed June 19, 2006, both of which are incorporated herein by reference as if fully set forth.

OLED devices, especially top emitting OLED devices as shown in FIG. 2, are optionally completed by depositing a thin film encapsulant, typically on a semitransparent

electrode. This construction of an OLED device provides an advantage; in particular it creates access to the critical high index device-air interface after the completion of device fabrication, enabling a lamination process for the application of the light extraction film. For top emitting OLED devices, embodiments include a light extraction film as described
5 above for bottom emitting OLED devices. Alternatively, the film can be designed to be the capping layer on a top emitting OLED structure when combined with a suitable high index adhesive to serve as the optical layer 130 in order to optically couple the OLED device to the light-extracting layer. The encapsulant material may itself serve as the index contrast material which backfills the nanostructures to form the light extraction layer.

OLED Solid State Lighting or Display Element

Top emitting OLED device 120 or bottom emitting OLED device 100 can also be used to implement an OLED solid state lighting or display element. In addition to the substrates identified above, examples of substrates useful in top emitting OLED solid state
15 lighting devices, including flexible metal foils, are described in the following papers, all of which are incorporated herein by reference as if fully set forth: D.U. Jin et al., "5.6-inch Flexible Full Color Top Emission AMOLED Display on Stainless Steel Foil," SID 06 DIGEST, pp. 1855-1857 (2006); and A. Chwang et al., "Full Color 100 dpi AMOLED Displays on Flexible Stainless Steel Substrates," SID 06 DIGEST, pp. 1858-1861 (2006).

FIG. 3 is a diagram illustrating a device 220 having spatially modulated OLED
20 devices for use in solid state lighting devices. Device 220 includes a substrate 222 supporting a plurality of OLED devices 223, 224, 225, and 226, each of which may correspond with the structures described above with respect to bottom or top emitting OLED display devices. Each of the OLED devices 223-226 can be individually controlled
25 as represented by lines 228 and 230, which would provide electrical connections to the anodes and cathodes in devices 223-226. Device 220 can include any number of OLED devices 223-226 with electrical connections, and substrate 222 can be scaled to accommodate them. The individual control of devices 223-226, via connections 228 and 230, can provide for spatial modulation of them such that they are individually or in
30 groups lighted in a particular sequence or pattern. Device 220 can be used in solid state light, for example, on a rigid or flexible substrate 222.

OLED Backlight Unit

FIG. 4 is a diagram of a top emitting OLED backlight unit 180 with light extraction film. Table 3 describes the exemplary elements of the backlight unit 180 and the arrangement of those elements, as identified by the reference numbers provided in FIG. 4. Each layer of backlight unit 180 can be coated on or otherwise applied to the underlying layer. Alternatively, bottom emitting OLEDs can also be used for backlight units.

Table 3 – OLED Backlight Unit with Light Extraction Film

Ref. No.	Type of Element
182	polarizer
184	optional prism layer
186	optional asymmetric reflective film
188	optional diffuser
189	substrate 1
190	low index structure
192	high index structure
194	optical coupling layer
195	optional thin film encapsulant layer
197	electrode 1
200	organic layers
202	electrode 2
204	substrate 2
206	auxiliary optical films
208	light extraction film

The light extraction film 208 in this embodiment is composed of low index structure 190 and high index structure 192. The light extraction film can optionally also include prism layer 184 and diffuser 188. Low index structure 190 and high index structure 192 can be implemented with the exemplary materials and constructions described above. The other elements of this embodiment, as provided in Table 3, can be implemented with the exemplary materials identified above. Layers 192 and 194 can alternatively be implemented with a single layer.

FIG. 5 is a diagram illustrating OLED devices used as a liquid crystal display (LCD) backlight unit 242 for an LCD panel 240. Backlight unit 242 may correspond with the structure 180. The backlight unit 242 can alternatively be implemented with the spatially modulated light panel shown in FIG. 3. LCD panel 240 typically includes the

entire LCD device except the backlight and drive electronics. For example, LCD panel 240 typically includes the backplane (subpixel electrodes), front and back plates, liquid crystal layer, color filter layer, polarizing filters, and possibly other types of films. Use of OLED devices as a backlight may provide for a thin, low power backlight for LCDs. An example of LCD panel components and a backlight unit are described in U.S. Patent No. 6,857,759, which is incorporated herein by reference as if fully set forth.

High Index/Low Index Regions and Surface Configurations

FIGS. 6-9 are diagrams depicting the possible spatial configurations of extraction elements. FIG. 6 illustrates a low index structure 250, having a regular pattern of nanostructures, with a high index structure 251 providing a planarizing layer over the nanostructures. The structures 250 and 251 are located between a low index substrate 246 and an OLED device region 247. FIG. 7 illustrates a low index structure 252, having an irregular pattern of nanostructures, with a high index structure 253 providing a planarizing layer over the nanostructures. The structures 252 and 253 are located between a low index substrate 248 and an OLED device region 249. In FIGS. 6 and 7, the low and high index structures are located between a substrate and an OLED device (light emitting) region.

FIG. 8 illustrates high index extraction elements 255 within a low index backfill region 254 with the low index region 254 providing the planarizing layer. The extraction elements 255 and backfill 254 are located between a low index substrate 260 and an OLED device region 259. FIG. 9 illustrates low index extraction elements 257 within a high index backfill region 256 with the high index region 256 providing the planarizing layer. The extraction elements 257 and backfill 256 are located between a low index substrate 261 and an OLED device region 262. In the embodiments shown in FIGS. 8 and 9, the extraction elements are concentrated in the evanescent zone. The layers shown in FIGS. 6-9 illustrate patterns and interfaces of the low index and high index structures described above.

FIGS. 10-14 are top view diagrams depicting possible surface configurations of extraction elements. FIGS. 10 and 11 illustrate regular periodic arrays of extraction elements. FIG. 12 illustrates a random distribution of extraction elements. FIG. 13 illustrates patterned regions of extraction elements. In particular, FIG. 13 illustrates portions of features, possibly in a regular pattern 264 or an irregular pattern 265,

interspersed within a different distribution of features 263. The regular or irregular patterns 264 and 265, respectively, along with the different distribution 263 may each have periodic, quasi-periodic, or random distributions of extraction elements. Such regions of patterns may be useful to optimize extraction of particular wavelengths of light at those regions, for example wavelengths corresponding with red, green, and blue light. In that case, the extraction regions can correspond and be aligned the red, green, and blue regions comprising pixels of a display device, and each extraction region can each be optimized to extract light from the corresponding red, green, and blue regions. FIG. 14 illustrates quasicrystal (tiled patterns) of extraction elements.

Examples of techniques for making extraction elements are described in U.S. Patent Application Serial No. 11/556719, filed November 6, 2006, which is incorporated herein by reference as if fully set forth. FIGS. 10-14 illustrate possible surface configurations of the nanostructures or other extraction elements described above with a backfill medium providing the planarizing layer over the nanostructures.

Additional techniques could include using lithography or interference lithography to expose nanoscale regions in a photosensitive polymer deposited on a flexible polymer web. After the exposure and development steps, the remaining photosensitive polymer would then define a nanostructured surface. Alternatively, this nanostructured photosensitive polymer surface can serve as an etch mask for exposure of the surface in an etching process. This etching technique would transfer the nanoscale pattern into the surface of the underlying polymer web or into a layer of a harder material, such as a silicon oxide, which had been deposited on the polymer web prior to the lithographic steps. The nanoscale surface defined in any of these manners could then be backfilled with an index contrasting medium to form the light scattering or diffracting layer.

Distributions of Nanoparticles for Light Extraction

This embodiment provides enhanced light extraction from an OLED using an index-contrasting film with randomly distributed high index nanostructures created by coating nanoparticles such as, for example, ITO, silicon nitride (Si_3N_4 , referred to here as SiN), CaO, Sb_2O_3 , ATO, TiO_2 , ZrO_2 , Ta_2O_5 , HfO_2 , Nb_2O_3 , MgO, ZnO, In_2O_3 , Sn_2O_3 , AlN, GaN, TiN, or any other high index materials on a substrate used in OLED fabrication or encapsulation, and then applying a low index coating, such as SiO_2 , Al_2O_3 , DLG, DLC, or

polymeric materials over the nanoparticles to provide the index contrast needed for scattering or diffraction efficiency and to planarize the surface. The randomly distributed nanostructures can be in contact with the substrate, proximate the substrate, grouped together in places, or in any random configuration proximate the substrate. A converse construction, potentially providing similar effectiveness, can comprise a random distribution of low index nanoparticles or nanostructures such as SiO₂, porous SiO₂, Borosilicate (BK), Al₂O₃, MgF₂, CaF, LiF, DLG, DLC, metal particles such as silver or gold particles, poly(methyl methacrylate) (PMMA), polycarbonate, PET, low index polymers, or any other low index materials with a contrasting high index filler material such as vapor deposited Si₃N₄ or a solvent-coated particle-filled polymer or a high index polymer. The substrate can optionally have one or more of the following coatings: an antistatic coating; or an adhesion promotion coating.

Coating processes such as dip coating, knife coating, dye coating, and roll-to-roll coating may be used for distributing the nanoparticles on the surface, and a similar process may be used to coat the backfill/planarization layer. The use of such techniques should render the process simple, easily scaled for manufacturing, and suitable for incorporation in film products manufactured via web line or roll-to-roll processes.

The roll-to-roll continuous process fabrication of light extraction films can include assembling monolayer or sub-monolayer coatings of low index nanoparticles on a plastic substrate, the applying an overcoat of high index material. An example of such a roll-to-roll process includes coating bare functionalized silica nanoparticles on plastic (PET) substrates and then overcoating those nanoparticles with a high index backfill material. The high index backfill materials can be obtained by loading epoxy or acrylate polymers with high index nanoparticles such as ZrO₂ or TiO₂. Additional high index materials are described in U.S. Patent Application Serial No. 12/262393, filed October 31, 2008, which is incorporated herein by reference as if fully set forth.

One particular manufacturing method involves applying nanoparticles having a first index of refraction onto a flexible substrate and overcoating a backfill layer on the nanoparticles to form a planarizing layer over them. The backfill layer comprises a material having a second index of refraction different from the first index of refraction. Preferably, a substantial portion of the nanoparticles are within an evanescent zone adjacent to a light emitting region of a self-emissive light source when the optical film is

located against the self-emissive light source. For example, a substantial portion of the nanoparticles can be in contact with the substrate to be within the evanescent zone, although in some embodiments the substantial portion of the nanoparticles in the evanescent zone need not be in contact with the substrate.

5 Applying the nanoparticles can involve coating the nanoparticles dispersed in a solvent onto the flexible substrate and allowing the solvent to evaporate before overcoating the backfill layer. Applying the nanoparticles can also involve applying them in dry form to the flexible substrate and then overcoating them with the backfill layer. An alternative to the method involves using substrate with a release agent, in which the
10 particles are applied to a substrate with a release agent, the substrate with the particles is applied to a device substrate with the particles in contact with it, and then the substrate is released to transfer the particles to the device substrate. One particular method involves a single process to coat the substrate with nanoparticles, dry it, coat the backfill layer, dry it again, and then cure the resulting film. Yet another particular method involves a first
15 process to coat the substrate with nanoparticles, dry it, and wind up the coating film, and then a second process to unwind the film, coat the backfill layer, dry it again, and then cure the resulting film.

Replication Method

20 One solution for forming a master tool having nanostructures involves the use of interference lithography. Regular periodic features as small as 100nm-150nm can be quickly written using this method. An advantage involves being able to write these patterns over larger areas, which can make the process more amenable to manufacturing.

 Production of a master tool for replication of the pattern can involve the following.
25 A substrate is coated with an overlayer of photoresist and then illuminated with one or more UV interference patterns to expose the resist in a regular pattern with the desired feature sizes. Development of the resist then leaves an array of holes or posts. This pattern can subsequently be transferred into the underlying substrate through an etching process. If the substrate material is not suitable to be used as a replication tool, a metal
30 tool can be made using standard electroforming processes. This metal replica would then become the master tool.

Another method involves forming a master tool having randomly-distributed nanostructures. A solution is prepared comprising nanoparticles of the appropriate size and with the appropriate surface modifications to prevent agglomeration. Methods for preparing such solutions are generally specific to the particular nanoparticles to be dispersed; general methods have been described elsewhere, including U.S. Patent No. 6,936,100 and Molecular Crystals and Liquid Crystals, 444 (2006) 247-255, both of which are incorporated herein by reference as if fully set forth. The solution is then coated onto a flexible substrate using one of a variety of solvent coating techniques, including knife coating, dip coating, spray coating, dye coating, or roll-to-roll coating. Pretreatment of the substrate using methods such as plasma etching may be required in order to assure uniformity of the solution coating. After solvent evaporation, the nanoparticles should be distributed in a way that is microscopically random but macroscopically uniform. As was the case with the uniform tool fabrication process described above, this pattern could then be transferred to an underlying substrate material through an etching or embossing process, or a metal tool can be made using standard electroforming processes.

In any of these cases, if a flat master tool has been produced, it or its replicas may then be tiled together to form a larger tool, as described in U.S. Patent No. 6,322,652, incorporated herein by reference as if fully set forth, or may be formed into a cylindrical tool for compatibility with a roll-to-roll replication process.

Once a master tool has been produced, replication of the structure into a polymer can be done using one of a variety of replication processes, including the 3C process. The substrate for this replication could be any polymer sheeting compatible with the chosen replication process; it may be already coated with the ultrabARRIER film as described above. Backfilling would then be performed downstream in, for example, a chemical vapor deposition (CVD) or sputtering process which can deposit a high index material, such as SiN or ITO, which is capable of filling the structures and then leveling out into a smooth layer. If SiN is used, this might then be followed by an ITO deposition process if a conductive upper layer is required. Alternatively, the downstream backfilling may be performed in a solvent coating process using suitable materials.

Examples

Example 1: 190 nm SiO₂ Nanoparticles with No 5 nm SiO₂ Nanoparticles (Comparative Example)

5 Dispersions of spherical silica nanoparticles with nominal diameter of 190 nm were obtained from the Nissan Chemical, 10777 Westheimer, Suite 830, Houston, TX 77042, U.S.A. The nanoparticles were treated with polyethylene oxide (PEO and dialyzed, 142971-86-4, 190 nm silica with PEO covered and dialyzed, 33.6% solids).

 The process details of treated 190 nm SiO₂ nanoparticles with PEO are as follows.
10 363 grams of Nissan MP-4540 (100 grams of silica) was added to a reaction vessel along with 7.5 grams of A1230 polyethylene oxide silane from Momentive Performance Chemicals. The mixture was reacted for 16 hours at 80°C. The reaction mixture was then dialyzed to remove any unreacted silane and other impurities. The solution was placed in a 2 Spectra/Por Dialysis membrane having a MWCO (Molecular Weight Cut-Off) of 12-
15 14,000. The material was dialyzed for 24 hours against constantly flowing tap water.

 The resulting nanoparticle suspension was diluted in 1 methoxy 2 propanol to produce suspensions having 2 percent by weight solids content. The 190 nm SiO₂ nanoparticle solution was coated on a PET substrate by a dip coating (coating speed: 65mm/min). It was shown from SEM images that there was a de-wetting issue resulting in
20 regions of the substrate having no particle coating.

Example 2: Improved Coating of 190 nm SiO₂ Nanoparticles Via Addition of 5 nm SiO₂ Nanoparticles (Treated)

 A 2wt% suspension of 190 nm SiO₂ nanoparticles was prepared as described in
25 Example 1, but with the addition of 1.1 wt% of 5 nm SiO₂ (treated by PEO: 147426-45-01, 5 nm silica particles treated with Silquest A1230). The 190 nm SiO₂ nanoparticles were coated on a PET substrate by a dip coating (coating speed of 65 mm/min as in Example 1). Through comparison of SEM images from Example 1 and this sample, the uniformity of the coating was shown to have been improved by adding the small
30 nanoparticles, although the de-wetting of the nanoparticles coating had not completely disappeared.

Example 3: Improved Coatings of 190 nm SiO₂ Nanoparticles Via Addition of Unmodified 5 nm SiO₂ Nanoparticles

A 2 wt% of 190 nm SiO₂ nanoparticles was prepared as described as in Example 1, but with the addition of 1.1 wt% of 5 nm SiO₂ (unmodified small 5 nm SiO₂ nanoparticles from Nalco Company, Nalco 2326). It was clearly shown from SEM images that unmodified small SiO₂ nanoparticles can significantly improve the large nanoparticle coating uniformity.

Example 4: 190nm SiO₂ Nanoparticles with 5 nm Modified SiO₂ Nanoparticles (Modified with Isooctyltrimethoxysilane and Methyltrimethoxysilane)

A 2wt % of 190 nm SiO₂ nanoparticles was prepared as described as in Example 1, but with the addition of 1.1 wt% of 5 nm SiO₂ nanoparticles modified with isooctyltrimethoxysilane and methyltrimethoxysilane. (The 5 nm nanoparticle powder was first dissolved in isopropanol to produce suspensions having 10 percent by weight solids content). As was shown through SEM images, the coating uniformity was improved, although the de-wet of the nanoparticles coating had not completely disappeared.

Example 5a: 440 nm SiO₂ Nanoparticles Coated by Roll-to-Roll Process without Small Nanoparticles (Comparative Example for Example 5b)

Dispersions of spherical silica nanoparticles with nominal diameter of 440 nm were obtained from the Nissan Chemical (Houston Office (Chemical Business), 10777 Westheimer, Suite 830, Houston, TX 77042, U.S.A.). The nanoparticle solution was diluted in 1 methoxy 2 propanol to produce a suspension having 5 percent by weight solids content. The 440 nm SiO₂ nanoparticles were coated on a corona-treated PET film (6-8mil thickness) by roll-to roll-process using a 5 mil coating gap (web speed of 10 fpm, ind. pump speed of 1.2 cc/min). The resulting coating was first dried in air at room temperature, then subsequently further dried at 180°F.

Example 5b: 440nm SiO₂ Nanoparticles Coated by Roll-to-Roll Process with Small Nanoparticles

2.5 wt% of 440 nm SiO₂ nanoparticles were prepared as in Example 5a, but then 1 wt% of modified 5 nm SiO₂ nanoparticles, prepared as in the Example 2, was added. The

440 nm SiO₂ nanoparticles were coated on the corona-treated PET film using the same conditions as in Example 5a.

Materials for Examples 6 and 7

Materials used in the Examples included silica nanoparticles of 93 nm nominal diameter obtained from the Nalco company, and dodecylbenzenesulfonic sodium salt (DS-10) surfactant obtained from Aldrich. Using these materials with different coating conditions, close-packed monolayers of nanoparticles, or sparse discontinuous layers, could be achieved.

Mono-layers of bare silica nanoparticles coated directly on a PET substrate for Examples 6 and 7

A silica nanoparticle dispersion produced by diluting a 2 wt% nanoparticles dispersion in H₂O to 1 wt% nanoparticles with DS-10 was coated on a corona-treated PET film (6-8 mil thickness) by the roll-to-roll process using a 5 mil gap (web speed of 10 fpm, dispersion delivery rate of 3 cc/min). The coating was dried in air at room temperature, and then subsequently it was further dried at 180°F. It was shown through a SEM photo of the resulting nanoparticle that a uniform and close-packed monolayer of silica nanoparticles was produced.

Discontinuous layer of bare silica nanoparticles coated directly on PET substrate for Examples 6 and 7

Silica nanoparticle dispersion as above was coated on corona-treated PET film (6-8 mil thickness) by the roll-to-roll process with a 5 mil gap and lower dispersion delivery rate (web speed of 10 fpm, dispersion delivery rate of 1.5 cc/min). The resulting coating was dried in air at room temperature, and subsequently further dried at 180°F on the web.

Example 6: Light-Extracting OLED Substrate with Silicon Nitride Overcoated Nanoparticles

In order to quantitatively evaluate the OLED efficiency enhancement due to the nanoparticle, 300 nm Si₃N₄ layer was applied over the silica nanoparticle coating using plasma-enhanced chemical vapor deposition (PECVD, Model PlasmaLab System100

available from Oxford Instruments, Yatton, UK). Conditions used in the Si_3N_4 deposition are shown in Table 4.

Table 4 - Conditions Used for Depositing Si_3N_4 Layer	
Reactant/Condition	Value
SiH_4	400 sccm
NH_3	20 sccm
N_2	600 sccm
Pressure	650 mTorr
Temperature	60°C
High frequency (HF) power	20 W
Low frequency (LF) power	20 W

- 5 The refractive index of the Si_3N_4 overcoating was measured using a Metricon Model 2010 Prism Coupler and was found to be 1.7. At the completion of the PECVD process, a low index scattering center with high index backfilling film had been generated.

Next, 110 nm of ITO was deposited on the silicon nitride through a 5 mm x 5 mm pixilated shadow mask to serve as the OLED anode. Subsequently, a simple green organic
 10 emitting layer and cathode were deposited to complete the OLED. The OLEDs were fabricated by standard thermal deposition in a bell-jar vacuum system. The OLED layers were deposited through a 40 mm x 40 mm shadow mask covering the 5 mm x 5 mm ITO pixels in the following order: TNATA:FeCl₃ (3000A, 5% FeCl₃)/NPD(400A)/Alq:C545T(300A, 2%)/Alq(200A)/7ALiF/Al.

- 15 The 5 mm x 5 mm shadow mask was then realigned, and 250 nm of Al metal was deposited to form the cathodes contacting the tops of the pixels. This process provided OLED devices containing several independently addressable 5 mm x 5 mm pixels with 4 pixels disposed over nanoparticles.

Electroluminescence measurements showed enhanced OLED light extraction from
 20 the nanoparticle coated pixels. An improvement of 50% at current densities between 2-20 mA/cm² was shown with this modification.

Example 7: Light Extracting OLED Substrate having Nanoparticles Overcoated by High Index Polymer Applied in Roll-to-Roll Process.

50-60 wt% of 10 nm ZrO_2 nanoparticles (refractive index of 1.85) were dispersed in acrylate to form a high refractive index (1.68) backfill polymer (obtained from Brant U. Kolb, 145840-77-38F). This high index polymer was mixed with 1 methoxy 2 propanol (10 wt%) and was then coated over the nanoparticles previously coated on PET by a roll-to-roll process with a 5 mil gap (web speed of 10 fpm, dispersion delivery rate of 1.6 cc/min). The resulting coating was dried in air at room temperature; subsequently, it was further dried at 180°F on the web. The target thickness of the high index polymer was 300 nm; SEM images indicated an actual thickness of about 300 nm in excellent agreement with the target thickness. The surface of the roll-to-roll coating was shown to be very smooth compared with Si_3N_4 deposited by plasma enhanced chemical vapor deposition.

Example 8: 93nm SiO_2 nanoparticles coated by roll-to-roll process with 60nm SiN overcoated on NPs as a stabilization layer**Preparation of nanoparticle coating by roll-to-roll process**

Dispersions of 93nm silica nanoparticles were obtained from the Nalco company. Polyvinyl alcohol (PVA, 98 mole % hydrolyzed, MW 78000) was obtained from Polysciences, Inc., and was dissolved in water with 1wt % solid content for the related experiments. Dodecylbenzenesulfonic sodium salt (DS-10) surfactant was obtained from Alderich.

A silica nanoparticle (NP) dispersion solution (93nm, 1wt%, 0.1-1wt% DS-10) was coated on PET film (6-8mil thickness) by a roll-to-roll process using a 5 mil gap (web speed of 10 fpm, dispersion delivery rate of 3 cc/min). The coating was dried in air at room temperature, and then subsequently it was further dried at 180°F.

Preparation of 60nm SiN stabilization layer by plasma-enhanced chemical vapor deposition

The silica-nanoparticle-coated film was then over-coated with a 60nm thick layer of silicon nitride by plasma-enhanced chemical vapor deposition (PECVD), for stabilization of the NPs (PECVD, Model PlasmaLabTM System100 available from Oxford

Instruments, Yatton, UK). The parameters used in the PECVD process are described in Table 5.

Table 5 - Conditions used for depositing SiN layer	
Reactant/Condition:	Value:
SiH ₄	400 sccm
NH ₃	20 sccm
N ₂	600 sccm
Pressure	650 mTorr
Temperature	100°C
High frequency (HF) power	20W
Low frequency (LF) power	20W

- 5 The refractive index of the SiN core layer was measured using a Metricon Model 2010 Prism Coupler, and was found to be 1.7.

Preparation of High-RI Coating Using 50 nm TiO₂ and ZrO₂ Nanoparticles

10 In a glass jar, 4.5 g of ZrO₂ HIHC prepared as above, 6.78 g of 50 nm TiO₂ dispersion, 24.4 g of 2-butanone, 16.62 g of 1-methoxy-2-propanol were mixed together. The mixture was stirred to form a homogenous white coating solution. The coating solution was applied on above sample (60nm SiN on 93nm nanoparticles/PET) using spin-coating at 4000 rpm for 40 seconds (Karl Suss spin coater, spin coater model CT62 from Suss MicroTec, Inc.), resulting in transparent high-index coatings. The coatings were

15 cured using a Fusion UV-Systems Inc. Light-Hammer 6 UV (Gaithersburg, Maryland) processor equipped with an H-bulb, operating under nitrogen atmosphere at 100% lamp power at a line speed of 30 feet/min (2 pass). The thickness of the high-index coating was measured to be approximately 150-200 nm. The refractive index of the high index coating is measured as 1.85 using Metricon Prism Coupler.

20 At the completion of the TiO₂-polymer backfill coating, a light extraction layer containing the low-index scattering nanostructure planarized with the high-index backfill was produced.

Fabrication of OLED

Approximately 110nm-thick ITO was deposited onto the backfill-coated NPs structures through a 5mm x 5mm pixilated shadow mask to define the anode geometry.

5 Subsequently, a simple green organic emitting layer and cathode were deposited to complete the OLED. The OLEDs were fabricated by standard thermal deposition in a vacuum system at base pressure of ca. 10^{-6} Torr. The following OLED construction was deposited: HIL(300nm)/HTL(40nm)/EML(30nm,6%)/Alq(20nm)/ LiF(1nm)/Al(200nm). After completion, the OLED was encapsulated with 3M encapsulation barrier film
10 employing SAES getter as a desiccant and oxygen scavenger in between the encapsulation film and the OLED cathode.

The 5mm x 5mm shadow mask was then realigned, and 200nm of Al metal was deposited to form the cathodes contacting the tops of the pixels. This process provided OLED devices containing several independently addressable 5mm x 5mm pixels with 4
15 pixels disposed over nanoparticles.

Electroluminescence measurements showed enhanced OLED light extraction from the nanoparticle coated pixels. An improvement of 50-100% was shown with this modification.

CLAIMS

1. A multifunctional optical film for enhancing light extraction from a self-emissive light source, comprising:

5 a flexible substrate;
a structured layer of extraction elements having a first index of refraction, wherein a substantial portion of the extraction elements are in optical communication with a light emitting region of the self-emissive light source when the optical film is located against the self-emissive light source, and wherein the extraction elements comprise first
10 nanoparticles of first size and second nanoparticles of a second size different from the first size; and

a backfill layer comprising a material having a second index of refraction different from the first index of refraction, wherein the backfill layer forms a planarizing layer over the extraction elements.

15 2. The multifunctional optical film of claim 1, further comprising a coating having at least one of the following functions: color filtering; color shifting; polarization modification; antireflection; light redirection; diffusion; or optical rotation.

20 3. The multifunctional optical film of claim 1, further comprising a coating applied to the substrate and having at least one of the following functions: antiabrasion; antismudge; hydrophobicity; or hydrophilicity.

25 4. The multifunctional optical film of claim 1, wherein the backfill layer material comprises one of the following: an inorganic material; an organic material; or a nanoparticle filled polymer material.

30 5. The multifunctional optical film of claim 1, wherein the elements comprise one of the following: a periodic or quasi-periodic array of features; a random distribution of features; or portions of periodic or quasi-periodic array of features interspersed within a different distribution of features.

6. The multifunctional optical film of claim 1, wherein the substrate comprises one of the following: a polymer film; a substantially optically transmissive material; or a barrier material.

5 7. The multifunctional optical film of claim 1, wherein the substrate has one or more of the following coatings: an antistatic coating; or an adhesion promotion coating.

8. The multifunctional optical film of claim 1, wherein the first size of the first nanoparticles is a diameter in the range of 60nm to 10 microns, and the second size of the
10 second nanoparticles is a diameter in the range of 3nm to 50nm.

9. The multifunctional optical film of claim 1, wherein the extraction elements comprise nanoparticles consisting of one or more of the following: metal oxide particles; organic polymer particles; metal particles; or composite particles.

15 10. A method for making an optical film for enhancing light extraction, comprising:
coating a layer of an organic material having a first index of refraction onto a flexible substrate;

imparting nanostructured features into the organic material to create a
20 nanostructured surface, wherein the nanostructured features comprise first nanostructured features of a first size and second nanostructured features of a second size different from the first size; and

applying a backfill layer to the nanostructured surface to form a planarizing layer on the nanostructured surface,

25 wherein the backfill layer comprises a material having a second index of refraction different from the first index of refraction, and

wherein a substantial portion of the nanostructured features are in optical communication with a light emitting region of a self-emissive light source when the optical film is located against the self-emissive light source.

11. The method of claim 10, wherein the nanostructured features comprise nanoparticles consisting of one or more of the following: metal oxide particles; organic polymer particles; metal particles; or composite particles.

5 12. The method of claim 10, further comprising coating a stabilization layer before applying the backfill layer.

13. The method of claim 10, further comprising curing the organic material having the nanostructured features.

10

14. The method of claim 10, wherein the imparting step comprises:
providing a master tool having nanostructured features; and
applying the flexible substrate with the layer of the organic material to the tool with the organic material applied against the tool to impart the nanostructures into the
15 organic material.

15. The method of claim 14, wherein the providing the master tool step comprises coating nanoparticles onto a surface of the master tool in order to create a texture on the surface.

20

16. The method of claim 10, further comprising using one of the following methods to apply the backfill layer to form the planarizing layer: liquid coating; vapor coating; powder coating; or lamination.

25 17. The method of claim 10, wherein the first size of the first nanoparticles is a diameter in the range of 60nm to 10 microns, and the second size of the second nanoparticles is a diameter in the range of 3nm to 50nm.

18. The method of claim 10, wherein the method is performed in a roll-to-roll process.

30

19. A method for making an optical film for enhancing light extraction, comprising:

applying nanoparticles having a first index of refraction onto a flexible substrate, wherein a substantial portion of the nanoparticles are in optical communication with a light emitting region of a self-emissive light source when the optical film is located against the self-emissive light source, and wherein the nanoparticles comprise first
5 nanoparticles of first size and second nanoparticles of a second size different from the first size; and

overcoating a backfill layer on the nanoparticles to form a planarizing layer over the nanoparticles, wherein the backfill layer comprises a material having a second index of refraction different from the first index of refraction.

10

20. The method of claim 19, wherein the applying step comprises:
coating the nanoparticles dispersed in a solvent onto the flexible substrate; and
allowing the solvent to evaporate before overcoating the backfill layer.

15

21. The method of claim 19, wherein the applying step comprises applying the nanoparticles in dry form to the flexible substrate.

22. The method of claim 19, wherein the applying step includes forming the nanoparticles as a monolayer on the flexible substrate.

20

23. The method of claim 19, wherein the substantial portion of the nanoparticles are in contact with the flexible substrate.

24. The method of claim 19, wherein the first size of the first nanoparticles is a
25 diameter in the range of 60nm to 10 microns, and the second size of the second nanoparticles is a diameter in the range of 3nm to 50nm.

25. The method of claim 19, wherein the method is performed in a roll-to-roll process.

30

26. The method of claim 19, further comprising coating a conformal stabilization layer over the nanoparticles.