Exhibit 5

(54) **QUANTUM DOT FILMS UTILIZING MULTI-PHASE RESINS**

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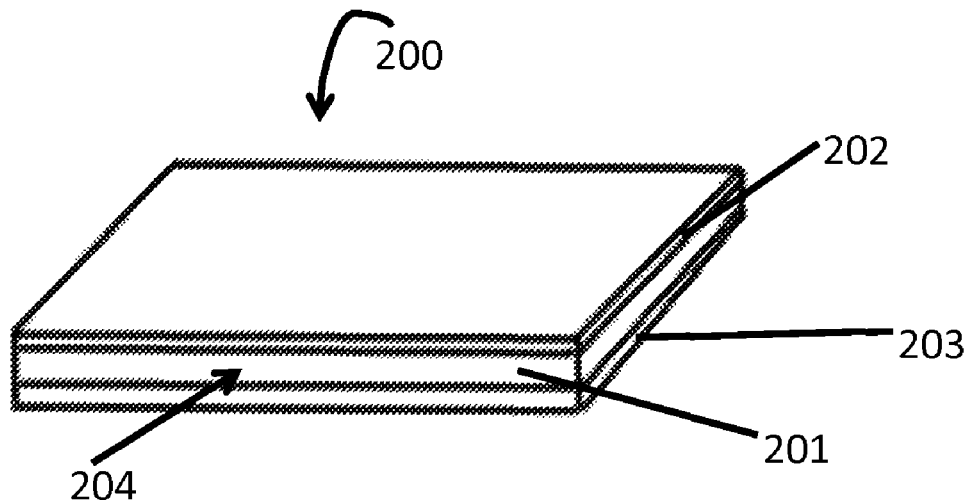
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C09K 11/02	(2006.01)

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(57) **ABSTRACT**

Multi-phase polymer films containing quantum dots (QDs) are described herein. The films have domains of primarily hydrophobic polymer and domains of primarily hydrophilic polymer. QDs, being generally more stable within a hydrophobic matrix, are dispersed primarily within the hydrophobic domains of the films. The hydrophilic domains tend to be effective at excluding oxygen.

1 Claim, 4 Drawing Sheets

100

105

106

102

101

103

104

Figure 1 (prior art)

200

202

203

201

204

Figure 2

Disperse QDs in Resin 1 Solution (401)

Combine Resin 1 Solution with Resin 2 Solution (402)

Mix Resin Solutions to Form Emulsion (403)

Laminate Emulsion Between Gas Barriers (404)

Cure Resin Emulsion to form 2 Phase Film (405)

Figure 4

300

303

301

302
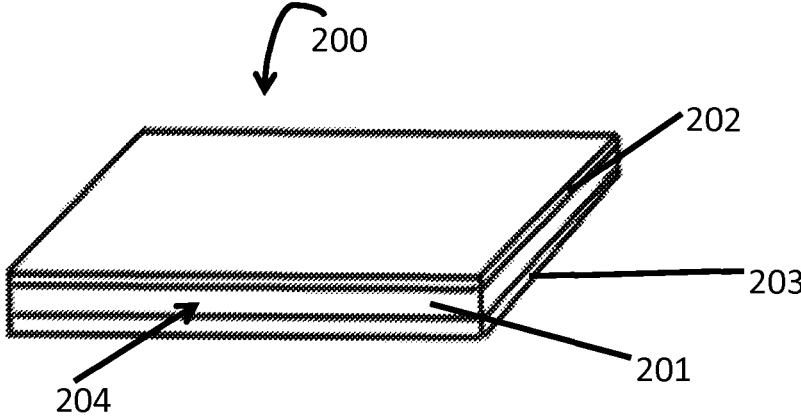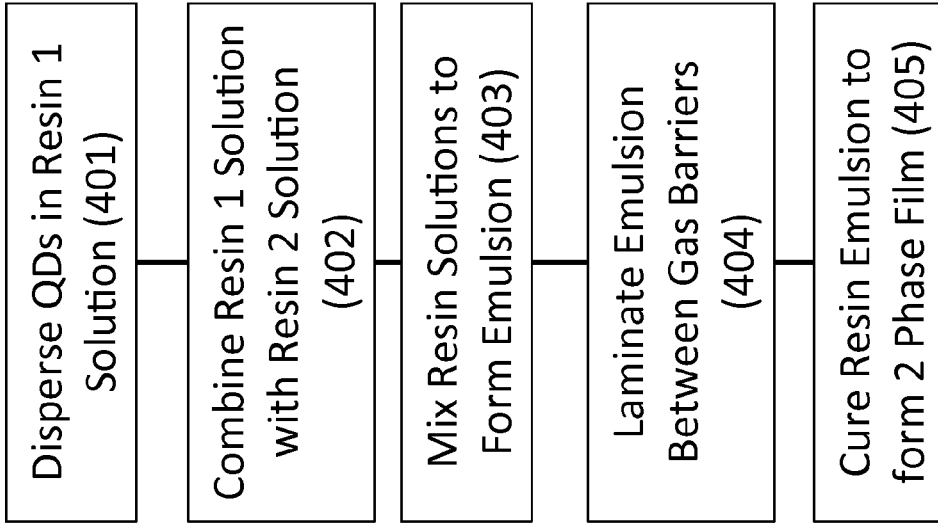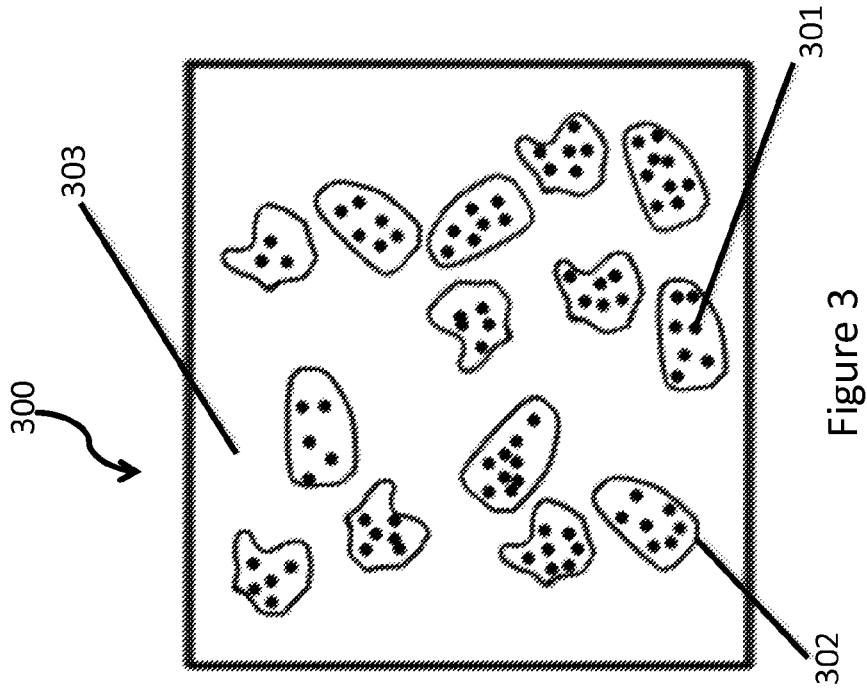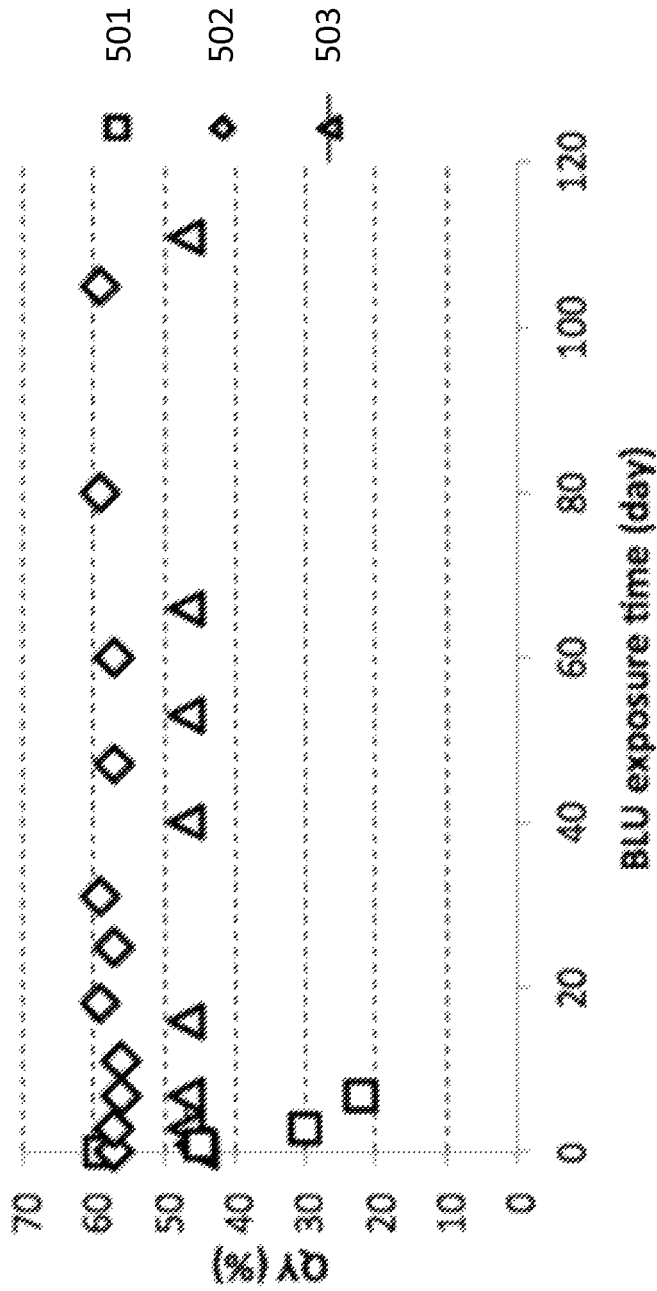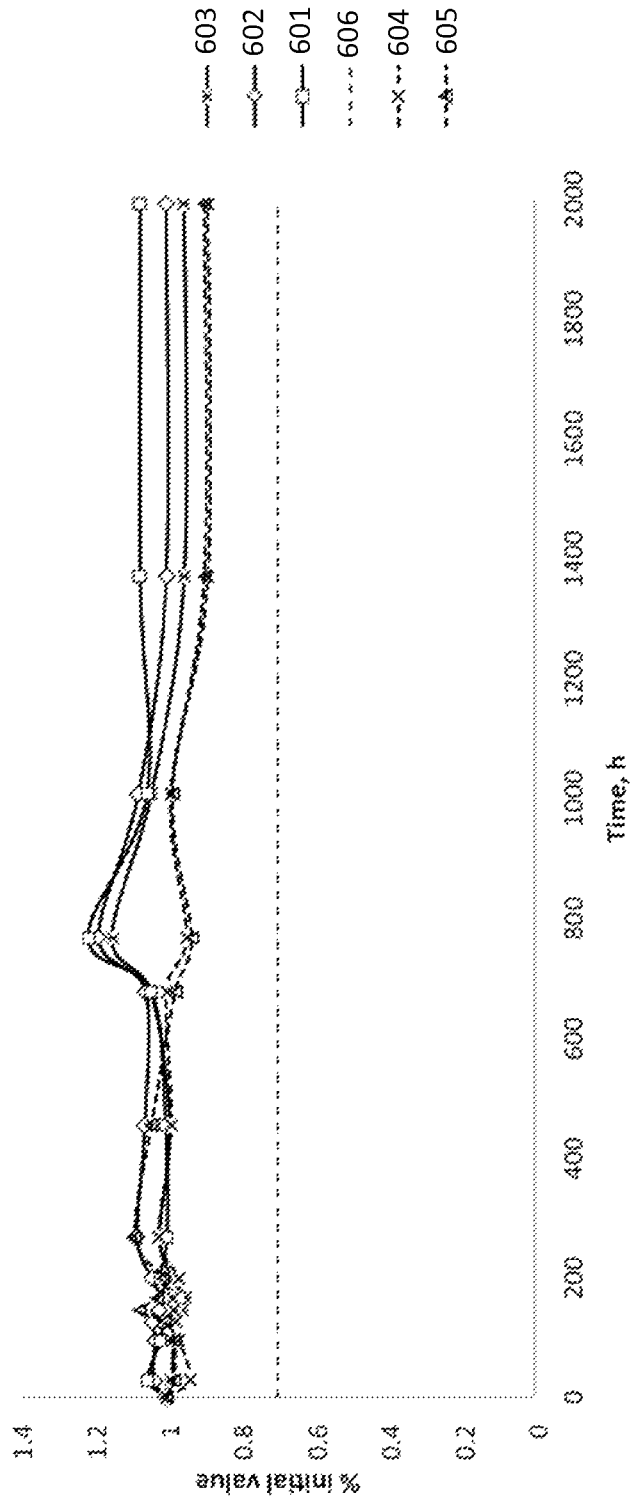
Figure 3

Figure 5

Figure 6

QUANTUM DOT FILMS UTILIZING MULTI-PHASE RESINS

FIELD OF THE INVENTION

The invention relates to materials comprising light emitting semiconductor quantum dots (QDs), and more specifically, multi-phase polymer films incorporating QDs.

BACKGROUND

Light-emitting diodes (LEDs) are becoming more important to modern day life and it is envisaged that they will become one of the major applications in many forms of lighting such as automobile lights, traffic signals, general lighting, liquid crystal display (LCD) backlighting and display screens. Currently, LED devices are typically made from inorganic solid-state semiconductor materials. The material used to make the LED determines the color of light produced by the LED. Each material emits light with a particular wavelength spectrum, i.e., light having a particular mix of colors. Common materials include AlGaAs (red), AlGaInP (orange-yellow-green), and AlGaInN (green-blue).

LEDs that produce white light, which is a mixture of fundamental colors (e.g., red, green and blue) or that produce light not available using the usual LED semiconductor materials are needed for many applications. Currently the most usual method of color mixing to produce a required color, such as white, is to use a combination of phosphorescent materials that are placed on top of the solid-state LED whereby the light from the LED (the "primary light") is absorbed by the phosphorescent material and then re-emitted at a different frequency (the "secondary light"). The phosphorescent material "down converts" a portion of the primary light.

Current phosphorescent materials used in down converting applications typically absorb UV or blue light and convert it to light having longer wavelengths, such as red or green light. A lighting device having a blue primary light source, such as a blue-emitting LED, combined with secondary phosphors that emit red and green light, can be used to produce white light.

The most common phosphor materials are solid-state semiconductor materials, such as trivalent rare-earth doped oxides or halophosphates. White emission can be obtained by blending a blue light-emitting LED with a green phosphor such as, $SrGa_2S_4:Eu_2^{2+}$ and a red phosphor such as, $SrSi_5Ni_8:Eu_2^{2+}$ or a UV light-emitting LED plus a yellow phosphor such as, $Sr_2P_2O_7:Eu^{2+}$; Mu^{2+}, and a blue-green phosphor. White LEDs can also be made by combining a blue LED with a yellow phosphor.

Several problems are associated with solid-state down-converting phosphors. Color control and color rendering may be poor (i.e., color rendering index (CRI)<75), resulting in light that is unpleasant under many circumstances. Also, it is difficult to adjust the hue of emitted light; because the characteristic color emitted by any particular phosphor is a function of the material the phosphor is made of. If a suitable material does not exist, then certain hues may simply be unavailable. There is thus a need in the art for down-converting phosphors having greater flexibility and better color rendering than presently available.

SUMMARY

Films containing QDs are described herein. The films may be used as components for LED lighting devices, particu-

larly, as phosphor films for down-converting light emitted from a solid-state LED semiconductor material.

The films are formed from two or more polymer materials, for example, two or more polymer resins. The films at least partially phase-separate, such that some domains within a film are primarily one of the polymer materials and other domains within the film are primarily the polymer material. One of the polymer materials is chosen to be highly compatible with the QDs. Another of the polymer materials is highly effective at excluding oxygen. As a result, the multi-domain films include QD-rich domains of QDs dispersed in the QD-compatible polymer, those domains being surrounded by QD-poor domains of the oxygen-excluding polymer. Thus, the QDs are suspended in a medium with which they are highly compatible and are protected from oxygen by the oxygen-excluding domains.

Methods of making such films are also described herein. According to some embodiments, QDs are suspended in a solution of a first polymer resin (i.e., a QD-compatible resin). The QD suspension is then added to a solution of the second polymer resin (the oxygen-excluding resin), yielding an emulsion. A film is formed of the emulsion, which can then be cured to form a solid film.

BRIEF DESCRIPTION OF THE DRAWINGS

The foregoing summary as well as the following detailed description will be better understood when read in conjunction with the appended drawings. For the purpose of illustration only, there is shown in the drawings certain embodiments. It is understood, however, that the inventive concepts disclosed herein are not limited to the precise arrangements and instrumentalities shown in the drawings.

FIG. 1 is a schematic illustration of a prior art use of a film containing QDs to down-convert light emitted by a LED.

FIG. 2 is a schematic illustration of a QD-containing polymer sandwiched between transparent sheets.

FIG. 3 is a schematic illustration of a two-phase film having a QD-compatible phase and an oxygen-excluding phase.

FIG. 4 is a flowchart illustrating the steps of making a two-phase film.

FIG. 5 is a plot of QD quantum yields in various films.

FIG. 6 illustrates stability studies of two-phase LMA/epoxy films.

DESCRIPTION

There has been substantial interest in exploiting the properties of compound semiconductor particles with dimensions on the order of 2-50 nm, often referred to as quantum dots (QDs) or nanocrystals. These materials are of commercial interest due to their size-tunable electronic properties that can be exploited in many commercial applications.

The most studied of semiconductor materials have been the chalcogenides II-VI materials namely ZnS, ZnSe, CdS, CdSe, CdTe; especially CdSe due to its tunability over the visible region of the spectrum. Reproducible methods for the large-scale production of these materials have been developed from "bottom up" techniques, whereby particles are prepared atom-by-atom, i.e., from molecules to clusters to particles, using "wet" chemical procedures.

Two fundamental factors, both related to the size of the individual semiconductor nanoparticles, are responsible for their unique properties. The first is the large surface-to-volume ratio. As particles become smaller, the ratio of the

number of surface atoms to those in the interior increases. This leads to the surface properties playing an important role in the overall properties of the material. The second factor is a change in the electronic properties of the material when the material is very small in size. At extremely small sizes quantum confinement causes the material's band gap to gradually increase as the size of the particles decrease. This effect is a consequence of the confinement of an 'electron in a box' giving rise to discrete energy levels similar to those observed in atoms and molecule rather than a continuous band as observed in the corresponding bulk semiconductor material. Thus, the "electron and hole" produced by the absorption of electromagnetic radiation are closer together than they would be in the corresponding macrocrystalline material. This leads to a narrow bandwidth emission that depends upon the particle size and composition of the nanoparticle material. QDs therefore have higher kinetic energy than the corresponding macrocrystalline material and consequently the first excitonic transition (band gap) increases in energy with decreasing particle diameter.

QD nanoparticles of a single semiconductor material tend to have relatively low quantum efficiencies due to electron-hole recombination occurring at defects and dangling bonds situated on the nanoparticle surface, which may lead to non-radiative electron-hole recombinations. One method to eliminate such defects and dangling bonds on the inorganic surface of the QD is to grow a second inorganic material, having a wider band-gap and small lattice mismatch to that of the core material, epitaxially on the surface of the core particle, producing a "core-shell" particle. Core-shell particles separate any carriers confined in the core from surface states that would otherwise act as non-radiative recombination centers. One example is QDs having a ZnS shell grown on the surface of a CdSe core.

Rudimentary QD-based light-emitting devices have been made by embedding colloidally produced QDs in an optically clear LED encapsulation medium, typically a silicone or an acrylate, which is then placed on top of a solid-state LED. The use of QDs potentially has some significant advantages over the use of the more conventional phosphors, such as the ability to tune the emission wavelength, strong absorption properties, improved color rendering, and low scattering.

For the commercial application of QDs in next-generation light-emitting devices, the QDs are preferably incorporated into the LED encapsulating material while remaining as fully mono-dispersed as possible and without significant loss of quantum efficiency. The methods developed to date are problematic, not least because of the nature of current LED encapsulants. QDs can agglomerate when formulated into current LED encapsulants, thereby reducing the optical performance of the QDs. Moreover, once the QDs are incorporated into the LED encapsulant, oxygen can migrate through the encapsulant to the surfaces of the QDs, which can lead to photo-oxidation and, as a result, a drop in quantum yield (QY).

One way of addressing the problem of oxygen migration to the QDs has been to incorporate the QDs into a medium with low oxygen permeability to form "beads" of such a material containing QDs dispersed within the bead. The QD-containing beads can then be dispersed within an LED encapsulant. Examples of such systems are described in U.S. patent application Ser. No. 12/888,982, filed Sep. 23, 2010 (Pub. No.: 2011/0068322) and Ser. No. 12/622,012, filed Nov. 19, 2009 (Pub. No.: 2010/0123155), the entire contents of which are incorporated herein by reference.

Films containing QDs are described herein. FIG. 1 illustrates a prior art embodiment 100, wherein a QD-containing film 101 is disposed on a transparent substrate 102. Such a film can be useful, for example, to down-convert primary light 103 from a primary light source 104 by absorbing primary light 103 and emitting secondary light 105. A portion 106 of primary light may also be transmitted through the film and substrate so that the total light emanating from the film and substrate is a mixture of the primary and secondary light.

QD-containing films, such as film 101 in FIG. 1, may be formed by dispersing QDs in a polymer resin material and forming films of the material using generally any method of preparing polymer films known in the art. It has been found that QDs are generally more compatible with hydrophobic resins, such as acrylates, compared to more hydrophilic resins, such as epoxies. Thus, polymer films made of QDs dispersed in acrylates tend to have higher initial quantum yields (QYs) than QD films using hydrophilic resins such as epoxy resins. However, acrylates tend to be permeable to oxygen, while epoxy resin polymers and similar hydrophilic polymers tend to be better at excluding oxygen.

One alternative for achieving high QY associated with QD-containing hydrophobic films, while also maintaining stability of the QY over time, is to insulate the film from oxygen by sandwiching the film between gas barrier sheets, as illustrated in FIG. 2. FIG. 2 illustrates a panel 200 having a polymer film 201 contained between gas barrier sheets 202 and 203. The polymer film 201 contains QDs dispersed throughout. Gas barrier sheets 202 and 203 serve to prevent oxygen from contacting the dispersed QDs. However, even in an embodiment as illustrated in FIG. 2, oxygen can permeate into the film at edges 204, resulting in a deterioration of the QY of the film.

One solution to this problem is to seal edges 204 with an oxygen barrier. However, doing so adds cost to the production of panel 200. Another option is to use a polymer 201 that is less permeable to oxygen. But as explained above, QDs are generally less compatible with such polymer resins, and therefore the optical properties of devices utilizing such polymers are less than ideal.

Multi-phase films utilizing at least a first phase (phase 1) resin that is compatible with the QD material and at least a second phase (phase 2) resin that is efficient at rejecting O_2 are described herein. FIG. 3 illustrate a plan view of such a film 300, wherein QDs 301 are dispersed in a first polymer phase 302, which is typically a hydrophobic material such as an acrylate resin. Regions of the first polymer phase are dispersed throughout a second polymer phase 303, which is typically an oxygen-impermeable material such as epoxy.

The multi-phase films described herein overcome many of the problems described above. The phase 1 resin is compatible with the QDs and therefore allows a high initial QY. The phase 2 resin is impermeable to oxygen, and therefore protects the QDs from oxidation without the need to seal the edges of the panel. As used herein, the term "film" includes, not only 2-dimensional (i.e. flat) sheets, as illustrated in FIGS. 1-3, but can also include 3-dimensional shapes.

FIG. 4 is a flowchart illustrating steps of a method of preparing multi-phase films as described herein. The QDs are dispersed in a solution of the phase 1 resin (or resin monomer) 401. As described above, the phase 1 resin is generally a hydrophobic resin, such as acrylate resins. Examples of suitable phase 1 resins include, poly(methyl (meth)acrylate), poly(ethyl(meth)acrylate), poly(n-propyl (meth)acrylate), poly(butyl(meth)acrylate), poly(n-pentyl (meth)acrylate), poly(n-hexyl(meth)acrylate), poly

(cyclohexyl(meth)acrylate), poly(2-ethyl hexyl(meth) acrylate), poly(octyl(meth)acrylate), poly(isooctyl(meth) acrylate), poly(n-decyl(meth)acrylate), poly(isodecyl(meth) acrylate), poly(lauryl(meth)acrylate), poly(hexadecyl(meth) acrylate), poly(octadecyl(meth)acrylate), poly(isobornyl (meth)acrylate), poly(isobutylene), polystyrene, poly (divinyl benzene), polyvinyl acetate, polyisoprene, polycarbonate, polyacrylonitrile, hydrophobic cellulose based polymers like ethyl cellulose, silicone resins, poly (dimethyl siloxane), poly(vinyl ethers), polyesters or any hydrophobic host material such as wax, paraffin, vegetable oil, fatty acids and fatty acid esters.

Generally, the phase 1 resin can be any resin that is compatible with the QDs. The phase 1 resin may or may not be cross-linked or cross-linkable. The phase 1 resin may be a curable resin, for example, curable using UV light. In addition to the QDs and phase 1 resin (or resin monomer), the solution of 401 may further include one or more of a photoinitiator, a cross-linking agent, a polymerization catalyst, a refractive index modifier (either inorganic one such as ZnS nanoparticles or organic one such as high refractive index monomers or poly(propylene sulfide)), a filler such as fumed silica, a scattering agent such as barium sulfate, a viscosity modifier, a surfactant or emulsifying agent, or the like.

The QD-phase 1 resin dispersion can then be mixed with a solution of the phase 2 resin (or resin monomer) 402. As explained above, the phase 2 resin is a better oxygen barrier than the phase 1 resin. The phase 2 resin is generally a hydrophilic resin. The phase 2 resin may or may not be cross-linkable. The phase 2 resin may be a curable resin, for example, curable using UV light. Examples of phase 2 resins include epoxy-based resins, polyurethanes-based resins, hydrophilic (meth)acrylate polymers, polyvinyl alcohol, poly(ethylene-co-vinyl alcohol), polyvinyl dichloride, silicones, polyimides, polyesters, polyvinyls, polyamides, enphenolics, cyanoacrylates, gelatin, water glass (sodium silicate), PVP (Kollidon). The solution of phase 2 resin may also include one or more of a photoinitiator, a cross-linking agent, a polymerization catalyst, a surfactant or emulsifying agent, or the like.

According to some embodiments, the phase 1-phase 2 mixture forms an emulsion 403, typically and emulsion of phase 1 resin suspended in phase 2 resin. The emulsion composition can be adjusted by adjusting the relative concentrations of phase 1 and phase 2 resins, the rate of stirring of the mixture, the relative hydrophobicity of the resins, and the like. One or more emulsifying agents, surfactants, or other compounds useful for supporting stable emulsions may be used.

According to certain embodiments, such as the embodiment illustrated in FIG. 2, the resin mixture is laminated between gas barrier films 404. Examples of gas barrier films include FTB3-50 (available from 3M, St. Paul, Minn.) and GX50W or GX25W (available from Toppan Printing Co., LT, Japan). Upon curing 405, the laminated resin film yields a polymer film having regions of phase 1 polymer, containing QDs, dispersed throughout phase 2 polymer, as illustrated in FIG. 3.

EXAMPLES

Example 1A

Green InP/ZnS QDs (120 Optical Density (OD)) were prepared as described in U.S. patent application Ser. No. 13/624,632, filed Sep. 23, 2011, the entire contents of which

are incorporated herein by reference. The QDs were added to a degassed vial, the toluene evaporated, and the resultant solid QD re-dispersed in degassed lauryl methacrylate (LMA, 2.64 mL) containing IRG819/IRG651 (Igracure®) photoinitiators (9/18 mg). Trimethylolpropane trimethacrylate (TMPTM) crosslinker (0.32 mL) was added. The mixture was further stirred for 30 min under nitrogen affording phase 1 resin. Films of QDs in phase 1 resin were laminated between 3M gas barrier layers on an area limited by a 19 mm×14 mm×0.051 mm plastic spacer. The film was cured with a Mercury lamp for 1 min. Stability testing of the QY of the QDs in phase 1 resin is represented by square data points in the plot illustrated in FIG. 5.

Example 1B

Two-phase resin was prepared by mixing 148 microliters of the phase 1 resin with 0.5 mL degassed epoxy (Epotek, OG142) and the mixture was mechanically stirred for 3 min at 100 rpm under nitrogen. 60 Microliters of the two-phase resin was then laminated between 3M gas barrier layers on an area limited by a 19 mm×14 mm×0.051 mm plastic spacer. The film was cured with a Mercury lamp for 1 min. Stability testing of the QY of the QDs in two-phase resin comprising acrylate (phase 1) and epoxy (Epotek OG142, phase 2) is represented by diamond-shaped data points in the plot illustrated in FIG. 5.

Example 2

Green InP/ZnS QDs (120 Optical Density (OD)) were prepared as described in U.S. patent application Ser. No. 13/624,632, filed Sep. 23, 2011. The QDs were added to a degassed vial and dispersed in degassed lauryl methacrylate (LMA, 2.64 mL) containing IRG819/IRG651 photoinitiators (9/18 mg). TMPTM crosslinker (0.32 mL) was added. The mixture was further stirred for 30 min under nitrogen affording phase 1 resin. Two-phase resin was prepared by mixing 148 microliters of the phase 1 resin with 0.5 mL degassed polyurethane acrylate (Dymax OP4-4-26032) and the mixture was mechanically stirred for 3 min at 100 rpm under nitrogen. 60 Microliters of the two-phase resin was then laminated between 3M gas barrier layers on an area limited by a 19 mm×14 mm×0.051 mm plastic spacer. The film was cured with a Mercury lamp for 1-5 min. Stability testing of the QY of the QDs in two-phase resin comprising acrylate (phase 1) and polyurethane acrylate (Dymax OP-4-26032, phase 2) is represented by triangle-shaped data points in the plot illustrated in FIG. 5.

Example 3

Green InP/ZnS QDs (120 Optical Density (OD)) were prepared as described in U.S. patent application Ser. No. 13/624,632, filed Sep. 23, 2011. The QDs were re-dispersed in degassed lauryl methacrylate (LMA, 1.2 mL) by stirring under nitrogen overnight. IRG819 photoinitiator (3 mg) was dissolved in 0.6 mL of the QD dispersion in LMA. TMPTM crosslinker (0.073 mL) was then added. The mixture was further stirred for 30 min under nitrogen, affording phase 1 resin with QD concentration at 89.2 OD/mL. Two-phase resin was obtained by mixing 67 microliters of phase 1 resin with 0.43 mL degassed epoxy (Epotek, OG142), upon which the mixture was mechanically stirred for 3 min at 100 rpm under nitrogen. 60 Microliters of the two-phase resin was then laminated between 3M gas barrier layers on an area

limited by a 19 mm×14 mm×0.051 mm plastic spacer. The films were cured with a Mercury lamp for 1 min.

Example 4

Green InP/ZnS QDs (120 Optical Density (OD)) were prepared as described in U.S. patent application Ser. No. 13/624,632, filed Sep. 23, 2011. The QDs were dispersed in degassed lauryl methacrylate (LMA, 2.64 mL) containing IRG819/IRG651 photoinitiators (9/18 mg) by stirring under nitrogen overnight. TMPTM crosslinker (0.32 mL) was added. The mixture was further stirred for 30 min under nitrogen affording phase 1 resin. Non-crosslinkable, non-viscous acrylate phase 2 resin was prepared by dissolving 10.1 mg IRG819 in deoxygenated glycidyl methacrylate (GMA, 1 mL). Non-crosslinkable, viscous acrylate phase 2 resin was prepared by dissolving polyvinylidene chloride (PVDC, Saran F310, 1.5 g) in deoxygenated GMA/IRG819/IRG651 (8.5 mL/57.5 mg/115.3 mg) solution. Two-phase resin was obtained by mixing 148 microliters of the phase 1 resin with 0.5 mL degassed phase 2 resin and the mixture was mechanically stirred for 3 min at 100 rpm under nitrogen. 60 microliters of the two-phase resin was then either added to the well of a 19 mm×14 mm glass plate or laminated between 3M gas barrier layers on an area limited by a 19 mm×14 mm×0.051 mm plastic spacer. The film was finally cured with Mercury lamp for 5 min.

Stability of Resin Films

FIG. **5** is a plot illustrating the quantum yield of resin films of QDs upon exposure to a blue backlight unit (BLU) for amounts of time (time, in days, denoted on the x-axis). The QY of green QDs in a single-phase LMA resin, as prepared in Example 1a above, is represented by square data points **501**. The single-phase resin film has an initial QY of about 60%, but the QY drops substantially during the first week of exposure.

Diamond-shaped data points **502** represent the QY of a two-phase film of LMA/epoxy resin containing QDs prepared as describe in Example 1b above. The initial QY of the LMA/epoxy two-phase film is also about 60%, but unlike that of the single-phase film, the QY of the two-phase film remains constant over the time period of the experiment. The stability of the QY indicates that the two-phase film effectively prevents oxidation of the QDs.

Triangle-shaped data points **503** represent QY a two-phase film of QDs in LMA/polyurethane acrylate, as prepared in Example 2 above. The initial QY of the LMA/polyurethane acrylate film is about 45% and remains stable for over three months. FIG. **6** illustrates stability studies of the two-phase LMA/epoxy film prepared in Example 1b. LED intensity **601**, efficacy **602**, photoluminescence intensity **603**, QD/LED ratio **604**, and % EQE **605** remain stable and above T70 **606** for at least 2000 hours.

Effect of Refractive Index of Phase 2 Resin

The phase 1 LMA resin used in the above Examples has a refractive index (RI) of 1.47. Table 1 illustrates the effect of the RI of the phase 2 resin effects the optical properties of the two-phase films.

Effect of Refractive Index of Phase 2 Resin (RI of phase 1 resin = 1.47).

Sample	Initial QY	Initial EQE	Phase 2 Resin	RI of cured Phase 2 Resin	2-phase QY	2-phase EQE
1	60	69	Urethane acrylate (OP4-4-20639)	1.47	60	72
2	60	69	Urethane acrylate (Dymax OP4-4-26032)	1.55	54	59
3	60	69	Epoxy (Epotek-OG142)	1.58	59	58

As shown in Table 1, when the RI of the first phase and that of the second phase are matched, the initial QY and EQE of the film is maximized. When there is mismatch between the RIs of the first and second phase resins, the initial QY and EQE of the film is reduced. Thus, it is beneficial, where possible, to use first and second phase resins that have closely matched RIs. According to some embodiments, the RIs of the two resins differ by less than about 5%. According to some embodiments, the RIs of the two resins differ by less than about 1%.

Accordingly, additives such as surfactants, viscosity modifiers, monomers, light scattering agents, and other inorganic surface tension modifiers may be used to adjust the RI of one or both phases so that the RIs match. Such additives may also be used to minimize chemical interaction between the phases. Moreover, chemical anti-oxidants (dilaurylthiodipropionate, octadecylsulfide, octadecanethiol, cholesteryl palmitate, Zinvisible, ascorbic acid palmitate, alpha tocopherol, BHA, BHT, octane thiol, lipoic acid, gluthathion, sodium metabisulfite, trioctyl phosphine (TOP), tetradecylphosphonic acids, polyphenols) may be added to one or both phases to minimize the degradation of QDs around the edges of the two-phase/gas barrier encapsulated QD films.

The inventive concepts set forth herein are not limited in their application to the construction details or component arrangements set forth in the above description or illustrated in the drawings. It should be understood that the phraseology and terminology employed herein are merely for descriptive purposes and should not be considered limiting. It should further be understood that any one of the described features may be used separately or in combination with other features. Other invented systems, methods, features, and advantages will be or become apparent to one with skill in the art upon examining the drawings and the detailed description herein. It is intended that all such additional systems, methods, features, and advantages be protected by the accompanying claims.

What is claimed is:

1. A method of preparing a film, the method comprising:
forming an emulsion comprising a first phase that comprises a first polymer and quantum dots and a second phase that comprises a second polymer;
depositing the emulsion between gas barrier sheets to form a film; and
curing the first and second polymers.

* * * * *