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Top-emission organic light emitting diodes with lower viewing angle dependence

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ABSTRACT

We obtained nanoporous polymer film which has 20–30% optical haze to suppress the viewing angle dependency of a top emission organic light emitting diode (TOLED) with strong microcavity effect. We controlled the sizes and density of nanopores by changing the spin coating condition such as spinning duration and spin rate in highly humid atmosphere up to 90% relative humidity condition. The resultant nanoporous polymer film has effectively reduced viewing angle dependency of microcavity TOLEDs without any serious decrease in total intensity of out-coupled light observed from the integrating sphere although the luminance observed from the front side was diminished slightly. Despite its negative effect on the efficiency toward the front direction, we could use those nanoporous polymer films as scattering media or diffuser layer on top of the encapsulation glass because it could change the strongly directed emission toward desired emission with Lambertian distribution.

1. Introduction

Active matrix organic light emitting diode (AMOLED) display is becoming a main display mode for mobile devices and continues to make progress toward low-power consumption television (TV) applications with high power efficiency, wide viewing angle, wide color gamut, and high-speed video rate [1–6]. However, such achievements have still been faced a lot of challenges of active matrix liquid crystal display (AMLCD) because the technology for AMLCD itself is still growing day by day. Thus, AMOLED should be differentiated by completely different properties in the competition with AMLCD. In that respect, an enormous attention is drawn to a next generation display with flexibility, so-called, flexible AMOLED because of its unquestionably superior bending property to that of thin film transistor-liquid crystal display (TFT-LCD). But, to realize a perfect image quality during bending or flexing, such a display should also have high resolution, high contrast ratio, wide color gamut, and desirable screen viewing angle, etc. Especially, the viewing angle property would be much more important in the flexible AMOLED display because the customer may want to watch the images without any distortion during flexing [6–10]. However, this is not easy issue because most of the current mobile AMOLEDs are prepared by top emission OLED (TOLED) structure with very strong microcavity. From this approach, we could realize more vivid and beautiful displays. In addition, this approach is indispensable because the unit pixel is comprised of several transistors and a couple of capacitors and those components and additional metal wirings should be buried under the OLED to realize high resolution display [1–6,11,12].

The TOLED itself is generally constructed with two metallic electrodes, a highly reflective anode and a semi-transparent cathode, and organic layers sandwiched between them [11]. The electrodes are parallel to each other and form a Fabry–Perot resonator, which results in the strongly resonant microcavity effect. Unfortunately, strong microcavity effect of the TOLEDs results in narrowed emission bandwidth with strong angle-dependent emission spectra, which is an obstacle to achieving display application such as large area television sets or flexible AMOLEDs for the future [5–12]. Thus, an angle-independent broadband emission is needed. Employing a low-reflectivity anode to alleviate the undesirable microcavity effect on the viewing angle characteristics has been proposed and demonstrated. Introducing a refractive-index-matching layer on top of the semitransparent cathode has also been demonstrated with optimized viewing characteristics by decreasing the reflectance of the cathode [10–12]. However, all such demonstrations are unable to eliminate the microcavity effect completely, but only minimize the microcavity effect by careful design of the metallic electrodes or its capping layer [13–18]. Despite its negative effect on the viewing angle characteristics, the microcavity resonance gives a positive effect on the emission efficiency through enhancing the spontaneous emission by continuous resonance [16–19].

In this work, we have introduced a nanoporous polymer films as scattering media which could reduce a viewing angle dependency.

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2. Experimental

2.1. Fabrication of nanoporous polymer film

For the preparation of the nanoporous polymer film, cellulose acetate butyrate (CAB, butyryl content: 50–54%) was purchased from ACROS and processed to prepare a diffuser layer. A 0.8 g of CAB was dissolved in THF (10 ml) and mixed homogeneously by vortex mixer for 10 min.

The resultant solution was deposited on the encapsulation glass by using a spin coating method. During spin coating process, the water vapor was directly supplied to spin coater by humidifier. The water vapor was supplied consistently to keep 90% relative humidity (RH) condition. After spinning and evaporation of all the residual solvents, the encapsulation glass with CAB film was completely dried for 10 min at room temperature. After finishing all the drying process, we investigated the morphology of polymer film with numbers of nanopores by using optical microscope (OLYMPUS, MX51) and FE-SEM technology (HITACHI, S-4700) [20].

The hazes of encapsulation glass with nanoporous polymer film were measured using a NDH-5000 haze meter from Nippon Denshoku Industries.

2.2. Device fabrication and characterization

2.2.1. Device fabrication

Clean glass substrates precoated with ITO/Ag/ITO layers were used to investigate top emission properties. Line patterns of anode materials were formed on glass by photolithography process. Bank layer was also formed on the anode and glass substrate by photolithography process to define the pixel aperture area by using photoresist. The glass substrates with anode as well as bank layer were cleaned by sonification in an isopropyl alcohol and acetone, rinsed in deionized water, and finally treated in a UV-ozone chamber. All organic materials were deposited by the vacuum evaporation technique under a pressure of $\sim 1 \times 10^{-7}$ Torr. The deposition rate of organic layers was about 0.5 Å/s. Then, lithium quinolate (LiQ) and magnesium (Mg): silver (Ag) (9:1) were successively deposited without breaking vacuum by the deposition rates of 0.15 and 2 Å/s, respectively.

2.3. Device characterization

The current density–voltage (*J*–*V*) and luminance–voltage (*L*–*V*) data of OLEDs were measured by Keithley SMU 2635A and Minolta CS-100A, respectively. Electroluminescence (EL) spectra and CIE coordinate were obtained using a Minolta CS-2000A spectroradiometer. The OLED area was 4 mm^2 for all the samples studied in this work. An integrating cube (IC2, StellarNet. Inc.) was connected to the spectrometer when integrated spectra for all emission angles were measured.

3. Results and discussion

3.1. Diffuser layer with nanoporous surface morphology

Nanoporous polymer films have attracted much attention due to their usefulness as supporting media in tissue engineering, membranes in separation process, templates for inorganic growth, dielectric materials for electronics devices, and optical materials [20–22]. We have chosen nanoporous polymer film as a diffuser (or scattering media) to reduce the viewing angle dependency of TOLED with strong microcavity effect.

The glass substrates with various hazes were shown in Fig. 1. We could prepare the various glass substrates with 20–40% of hazes by simple spin coating of CAB solution at 1000–2000 rpm for 30 s in the 90% RH condition. The haze could be controlled by changing of the spinning rate or duration. The CAB films formed by this process were shown in Fig. 1, and they showed transmittance of 87%, 88%, and 90%, respectively, in the order from Fig. 1(a)–(c). However, we selected only 20 and 30% haze conditions to fabricate scattering TOLEDs because immoderate haze could blur pixels and ruin the resolution of the real devices although all the CAB films we prepared show reasonably high transmittance levels. The preparation of glass substrate with haze value less than 10% was difficult due to a lack of process repeatability.

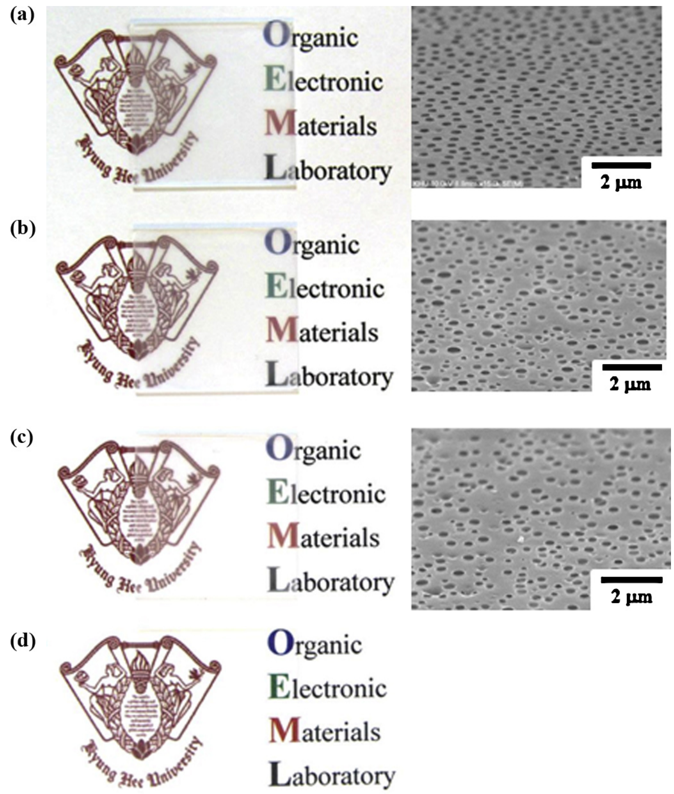

Fig. 1. Pictures of hazy glasses and SEM images of corresponding nanoporous polymer film of each hazy glass. The glasses with nanoporous polymer film show haze of (a) 40%, (b) 30%, and (c) 20%, respectively. (d) image of bare glass as a reference. Area of glass substrates is 25 mm × 25 mm.

Fig. 2 shows the SEM (scanning electron microscope) images of top surfaces and cross-sections of CAB films prepared by spin-coating under highly humid environment (RH = 90%) as aforementioned. We formed those layers on top of the encapsulation glass to investigate the possibility to convert the strongly directed emission into desired emission like Lambertian distribution. Fig. 2(a) shows the randomly formed nanopores on the surface of CAB film. The diameters of those nanopores were easily controlled from 200 to 400 nm while the distances between those nanopores could also be controlled from 50 to 400 nm for the desirable interference of the visible light emitted from the OLED devices [Fig. 2(a) and (b)]. Very interestingly, those nanopores were formed only on the surface of the polymer film as shown in Fig. 2(c). The film formed in this condition showed haze and transmittance up to ~40% and 87%, respectively.

3.2. Device characteristics

Fig. 3 shows the perspective images of the TOLED devices fabricated in this study. We used Indium tin oxide (ITO)/silver (Ag)/ITO as an anode, 2,2′,7,7′-tetrakis(diphenylamino)-9,9′-spirobifluorene (spiro-TAD) as hole transport layer,