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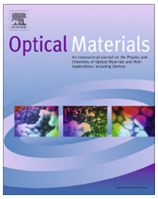

Dimmable sunlight-like organic light emitting diodes with ultra-high color rendering index

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ABSTRACT

We propose novel dimmable sunlight-like white organic light-emitting diodes that were fabricated using three luminophores to form an emitting spectrum similar to black body radiation at 2250 K with ultra-high color rendering index (CRI) value of 91, which nearly remained the constant at various luminance values ranging from 100 to more than 2500 cd/m^2 at Commission Internationale de l'Eclairage chromaticity coordinates of (0.51,0.41). Introducing charge modification layers suppressed the energy transfer between the emitting material layers and increased the probability of carrier recombination. Moreover, we reveal that covering long-wavelength ranges played a vital role in achieving high CRI values; the CRI values of a spectrum artificially shifted toward a long-wavelength direction (from 610 to 620 nm) remained constant, whereas those of a spectrum shifted toward a short-wavelength direction (from 610 to 600 nm) dropped to 79.

1. Introduction

White organic light-emitting diodes (WOLEDs) have recently attracted considerable attention because of their low cost, low power consumption, and potential applicability in large size products. Furthermore, WOLEDs are considered a promising next-generation solid state lighting source [1–3]. In particular, because the color temperature and emitting spectrum of WOLEDs can be easily modified, such devices are advantageous for creating light sources replicate sunlight, and their unique features render them advantageous for niche markets. Currently, numerous artificial lighting applications are implemented, and most of such applications are not human-friendly because numerous lighting sources contain strong radiation with intense energy (i.e., high color temperatures), which considerably influence macular health and human hormones and even lead to cancer [4,5]. In addition, lack of exposure to sunlight because of prolonged indoor working shifted considerably influence human psychology and physical state, which causes myopia and seasonal affective disorder [6–13]. OLEDs can replicate sunlight at low color temperatures using organic materials with broad emitting spectra to generate effective and natural lighting environments for humans. Furthermore, an excellent color rendering index (CRI) involving a wide range of luminance values is a key characteristic of lighting systems because it enables them to reflect true object colors in specific application, such as dimmable lighting for museums or surgery rooms. To generate safe and high-quality lighting products, numerous groups have thoroughly investigated and reported approaches for fabricating WOLEDs, and some of such approaches involve using blending luminophores [14–16], multilayer emitter [17–23], or tandem structure [24–28]. Another groups have also devoted themselves to the color-stability devices for dimmable lighting applications [29–31]. However, most studies have focused on investigating white light instead of nature-like lighting sources to match Commission Internationale de l'Eclairage (CIE) chromaticity coordinates of (0.33,0.33). Recently, Jou et al. [32] revealed a sunlight-style OLED with a tunable color temperature between 2500 and 8000 K; this device can reflect diverse sky situations at various driving voltages. Yu et al. [33] reported a sunlight-like and color tunable OLED with a high CRI (i.e., 89). This OLED applies four luminophores to create sunlight-like emitting spectra.

This paper presents novel dimmable and sunlight-like WOLEDs demonstrating high chromatic stability and a high CRI value. The proposed WOLEDs were developed using only three luminophores and charge modification layers. The WOLEDs exhibited emissions similar to black body radiation at 2250 K which reached low color temperatures and demonstrated an excellent CRI value of 91 at luminance values ranging from 100 to more than 2500 cd/m^2. Moreover, we conducted a peak shift simulation and determined

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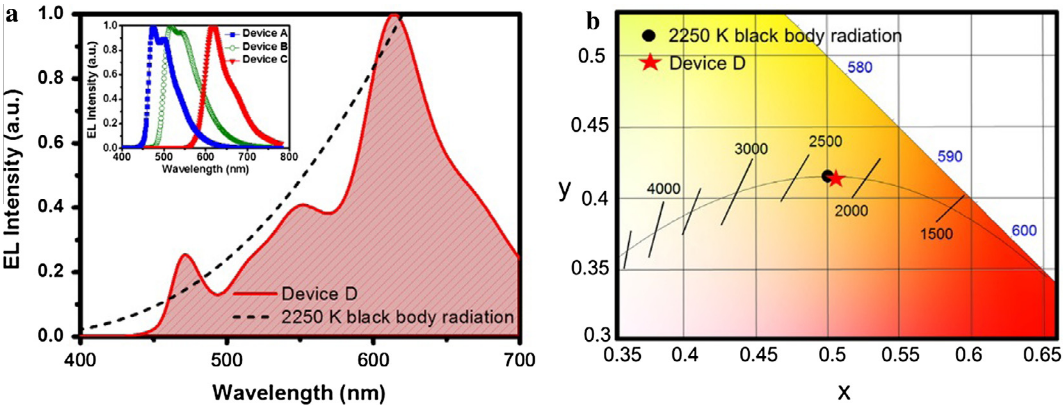

Fig. 1. (a) Comparison of EL spectra between device D and black body radiation at 2250 K. The inset indicates EL spectra of device A, B, and C. (b) CIE chromaticity coordinates of device D(0.51, 0.41) and black body radiation at 2250 K(0.50, 0.42).

that reddish luminophores are key components enabling WOLEDs to achieve high CRI values. The simulation indicated that although the spectral profile did not change considerably, the spectral occupations of the long-wavelength peak revealed the noticeable deviation of CRI values.

2. Experimental

Indium tin oxide (ITO) coated on glass substrates served as WOLED anodes, which were patterned using a photolithography process and cleaned in an ultrasonic bath with detergent and deionized water. After UV-ozone treatment, the substrates were sent to a high-vacuum system with a pressure of less than 5×10^{-6} Torr for evaporation of organic materials and metals. To remove moisture from the substrates, they were baked at 150 °C for 20 min in a vacuum system before material evaporation. In this experiment, 1,4,5,8,9,11-hexaazatriphenylenehexacarbonitrile (HATCN) was used as a charge generation layer to enhance carrier injection [34]. N,N′-Di(1-naphthyl)-N,N′-diphenyl-(1,1′-biphenyl)-4,4′-diamine (NPB) and tris(4-carbazoyl-9-ylphenyl)amine (TCTA) were used as hole transport layers; 4,4,NN′-dicarbazolebiphenyl (CBP), is a bipolar host material, was separately blended with a blue-light luminophore of bis[2-(4,6-difluorophenyl)pyridinato-C^2,N](picolinato) iridium(III) (FIrpic), a green-light luminophore of tris[2-phenylpyridinato-C^2,N]iridium(III) (Ir(ppy)$_3$), and a red-light luminophore of PR-06 synthesized by the Material and Chemical Research Laboratories of the Industrial Technology' Research Institute(ITRI). Furthermore, N,N′-Di(1-naphthyl)-N,N′-diphenyl-(1,1′-biphenyl)-4,4′-diamine (TBPi), 8-hydroxyquinolatolithium (Liq), and aluminum were used as an electron transport layer, an electron injection layer and cathode, respectively. Subsequently, all the devices were fabricated using the mentioned materials. To optimize the performance of the devices, the device structure was based on the energy level of highest occupied molecular orbital and lowest unoccupied molecular orbital of each material. All the organic materials were deposited using thermal evaporation at a rate of 0.05 nm/s except for Liq, which was deposited at a rate of 0.01 nm/s. The metal cathode of aluminum was evaporated at a rate of 0.3 nm/s. The overlap area of this metal cathode with ITO was 3 mm × 3 mm, and this area served as an active area. The current-voltage-brightness characteristics were measured using a Keithley 2400 source-meter and Konica Minolta CS-2000 spectrometer in ambient atmosphere at room temperature. All the device fabrication and measurement were processed in a clean room to prevent the contamination of particles.

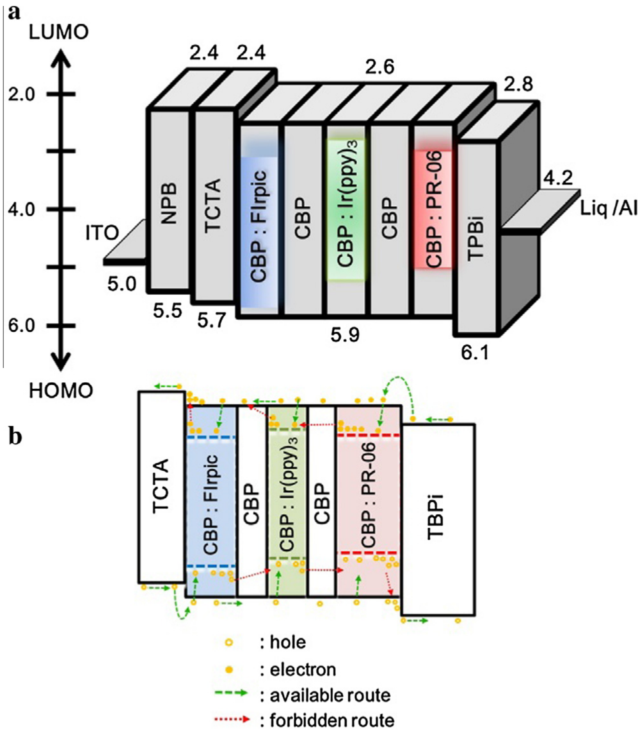

Fig. 2. (a) Device structure and energy level of materials used in device D. (b) Mechanism of the CBP charge modification layer for blocking carrier transport among emitters to stabilize emitting color and enhance carrier recombination.

3. Results and discussion

To evaluate the properties of these three luminophores used to create an emitting spectra in the emitting material layers (EML), electroluminescent (EL) spectra of devices fabricated using each of those luminophores were validated. Fig. 1(a) (inset) illustrates the EL spectra of devices A, B, and C, indicating that the structures of these devices are HATCN (30 nm)/TCTA (10 nm)/CBP:20% FIrpic (15 nm)/TPBi (20 nm)/Liq (1 nm)/Al (150 nm), HATCN (30 nm)/TCTA (10 nm)/CBP:5% Ir(ppy)$_3$ (15 nm)/TPBi (20 nm)/Liq (1 nm)/Al (150 nm), and HATCN (30 nm)/TCTA (10 nm)/CBP:8% PR-06 (15 nm)/TPBi (20 nm)/Liq (1 nm)/Al (150 nm), respectively. To create devices demonstrating similar missions to black body radiation at 2250 K, the proportion of the red[1] EML should dominate the radiation spectrum of the device, followed by the green EML. This can be

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[1] For interpretation of color in Figs. 1 and 3, the reader is referred to the web version of this article.