Organic Electronics 12 (2011) 923–935

Contents lists available at ScienceDirect

Organic Electronics

journal homepage: www.elsevier.com/locate/orgel

Optical simulation and optimization of ITO-free top-emitting white organic light-emitting devices for lighting or display

Jian Ma [a,b], Xuecheng Piao [a], Jian Liu [a], Letian Zhang [a,*], Tianyu Zhang [a], Mo Liu [a], Tong Li [a], Wenfa Xie [a,*], Haining Cui [b]

[a] State Key Laboratory on Integrated Optoelectronics, College of Electronic Science and Engineering, Jilin University, Changchun 130012, People's Republic of China
[b] Department of Physics, Jilin University, Changchun 130023, People's Republic of China

ARTICLE INFO

Article history:
Received 16 January 2011
Received in revised form 25 February 2011
Accepted 26 February 2011
Available online 12 March 2011

Keywords:
Top-emitting
White OLED
Lighting
Display

ABSTRACT

We present a simulation of the optical properties of ITO-free top-emitting white organic light-emitting devices (TEWOLEDs). Metals (Al, Ag, Mo, Cu, Au, Sm) are used as anode or cathode depending on their work functions. Besides, devices with 1D metallic–dielectric photonic crystal anode are also demonstrated. The influence of the capping layer or the metallic–dielectric multilayer structure on the optical properties (such as efficiency, angular emission characteristics, color gamut and color rendering index) of the devices has been investigated. The results indicated that TEWOLEDs can be used as lighting with high color rendering index or as a display with wide color gamut by carefully designing the structure of the devices.

1. Introduction

Top-emitting organic light-emitting device (TEOLEDs) [1–5], giving off light through a transparent or semitransparent top electrode, can fabricate on arbitrary substrates and provide a high-aperture-ratio display. High-conductivity and transparent indium tin oxide (ITO) is used for the bottom emitting OLEDs. However, indium is a relatively scarce element and ITO film lacks mechanical stability. Thus, ITO-free TEOLEDs will be superior to the bottom ones.

White OLED (WOLED) is of interest due to its application in full-color display or lighting [6–10]. For lighting applications, in contrast to bottom-emitting WOLED, progress of top-emitting WOLED (TEWOLED) has fallen behind [11–13]. The key challenge is the microcavity effect present in the TEOLEDs with a semitransparent metal top cathode [14–16], leading to narrow EL spectra and angular color non-uniformity that are not beneficial for lighting devices. It can be overcome by applying a light outcoupling layer on the top cathode to increases the transmission of the top electrode and reduce the microcavity effects [17–19]. Besides, high color rendering index (CRI) is also important for the lighting devices, however, there are few reports on a high CRI TEWOLED [12] and no report on the CRI angular characteristics of the TEWOLED.

For full-color display applications, the combination of WOLED and color filters is the most promising technology. Nevertheless, WOLEDs usually exhibit broad EL spectra and match poorly with the transmission spectra of the color filters [20,21]. Thus, RGB colors filtered from WOLEDs are often less saturated and the color gamut of the display is narrow. Microcavity TEWOLEDs with three narrow emission peaks occurring at desired RGB wavelengths could well match the transmission spectra of RGB color filters to achieve a wide color gamut display, especially for a near-to-eye display in which angular performance is less important. However, there are few systemic studies on the microcavity effect on the color gamut and color shift of the display based on TEWOLEDs [22].

In this paper, we present a simulation of the optical properties of ITO-free top-emitting white organic light-emitting devices for lighting or display applications

* Corresponding authors.
E-mail addresses: zlt@jlu.edu.cn (L. Zhang), xiewf@jlu.edu.cn (W. Xie).

1566-1199/$ - see front matter © 2011 Elsevier B.V. All rights reserved.
doi:10.1016/j.orgel.2011.02.021

systemically. We discuss two types of TEWOLEDs according to the anode: (1) metal and (2) 1D metallic–dielectric photonic crystal. Our results indicated that TEWOLEDs could be used as lighting devices with high CRI and stable angular color uniformity or displays with wide color gamut by carefully designing the structure of the devices.

2. Review of current developments in TEWOLEDs

Extensive efforts have focused on eliminating the microcavity effects in TEWOLEDs. Transparent conductive oxide like ITO and semitransparent metals with or without light outcoupling layer are commonly used in TEWOLEDs. In 2005, Kanno et al. [23] fabricated a TEWOLED with Ni anode and ITO cathode. The power efficiency and the CIE coordinates of the device are 9.8 lm/W ± 1.0 lm/W and (0.42, 0.39), respectively. There is only weak angular dependence in the spectra, and the CIE coordinates shifted by (0.02, −0.01) from 0° to 60°.

However, the ITO sputtering technology is hard to control and more researchers would like to use metal films as cathodes. In 2005, Hsu et al. [17] reported a TEWOLED employing a SnO_2 index-matching layer on the Ca (5 nm)/Ag (15 nm) cathode. A near-white light emission (0.31, 0.47) with an efficiency of 22.2 cd/A is obtained and the emission shows less angular dependence. In 2007, Zhu et al. [18] reported a TEWOLED with Ca (6 nm)/Au (15 nm)/Alq_3 (50 nm) cathode. The device shows a maximum power efficiency of 12.8 lm/W. There is less angular dependence in the spectra, and the CIE shifted by (0.01, −0.03) from 0° to 60°. In 2008, Lee and Tseng [24] reported a nearly Lambertian TEWOLED with low-reflectivity molybdenum (Mo) anode and Al (1.5 nm)/Ag (17.5 nm)/N,N′-bis-(1-naphthyl)-N, N′diphenyl-1,1-biphenyl-4,4′diamine (NPB, 30 nm) as cathode. A white emission with efficiency of 3.7 cd/A and CIE coordinates of (0.33, 0.39) is obtained, and the emission shows less angular dependence. In 2010, Freitag et al. [12] demonstrated a TEWOLED with Al (60 nm) as anode and Al (1 nm)/Ag (15 nm)/NPB (50 nm) as cathode. The emission shows CIE coordinates of (0.420, 0.407) at approximately 1000 cd/m^2, the power efficiency and color rendering indices (CRI) are 8.0 lm/W and 75.6, respectively. However, the light emission from the device exhibits a rather strong directionality, rather than a Lambertian behavior. Currently, Xie et al. [11] reported a TEWOLED with Cu anode and Al (2 nm)/Ag (18 nm)/4,4′,4″-tris-(3-methylphenyl-phenylamino)-tripheny-lamine (m-MTDATA, 50 nm) cathode. The device reaches high efficiencies of 17.6 lm/W at a current density of 10 mA/cm^2, and low voltage of 4.4 V at 1000 cd/m^2. And the emission shows less angular dependence.

TEWOLEDs utilizing microcavity effect also have been reported. In 2008, Kim et al. [25] reported the TEWOLED with Ag/ITO anode and Al (2.0 nm)/Ag (20 nm)/ITO (63 nm)/SiO_2 (42 nm) cathode. By varying the microcavity length of TEOLEDs through the variation of the anode ITO thickness and, by optimizing the dopant DCJTB concentration and the thickness of the emissive 4,4′-bis(2,2′-diphenylvinyl)-1,1′-biphenyl (DPVBi) layer, an EL spectrum composed of two complementary wavelengths close to white light could be obtained. But the light-emitting efficiency was merely about 1.4 lm/W and there is no report on the angular dependence characteristics in the EL spectra.

In 2009 and 2010, we reported the microcavity TEWOLED with 1D metallic–dielectric photonic crystal anode and Al (1 nm)/Ag (20 nm)/MoO_x (35 nm) cathode [13,26]. By simply adjusting the thickness of the dielectric layer, multiple-peak TEWOLEDs with EL peaks at desired wavelengths were achieved. However, the emission is obvious angular dependence, for example, the CIE coordinates shifted by (0.06, 0.01) from 0° to 60° in a two-peak TEWOLED.

In 2010, Wang et al. [27] reported a microcavity inverted TEWOLED with Al (100 nm) anode and Ag (24 nm)/NPB (80 nm) cathode. The device showed an efficiency of 5.6 cd/A and the CRI is 68. However, the emission is severe angular dependence, and the CIE coordinates shifted by (0.06, 0.1) from 0° to 60°.

3. Results and discussion

The approximate theoretical spectrum for emission in the microcavity device can be calculated following the approach of Deppe et al. [28]. The emission properties of TEWOLEDs are investigated using the optical module of the OLED simulation software SimOLED [29].

In our simulation, two kinds of devices with the following configurations were prepared: Blue–yellow (BY) device: anode/MoO_x (1.5 nm)/m-MTDATA (28 nm)/NPB (10 nm)/DPVBi (15 nm)/4,4-N,N-dicarbazole-biphenyl (CBP, 5 nm)/CBP:bis(2-(2-fluorphenyl)-1,3-benzothiozolato-N,C2′) iridium (acetylacetonate) [(F–BT)$_2$Ir(acac)] (7 nm)/4,7-diphenyl-1,10-phenanthroline (Bphen, 30 nm)/cathode; Red–green–blue (RGB) device: anode/MoO_x (1.5 nm)/m-MTDATA (25 nm)/NPB (10 nm)/DPVBi (15 nm)/CBP (2 nm)/CBP:Ir(ppy)$_3$ (5 nm)/CBP:Ir(piq)$_2$(acac) (5 nm)/4,7-diphenyl-1,10-phenanthroline (Bphen, 35 nm)/cathode. According to the energy levels of the materials, we assume that the excitons will form at the interfaces of NPB/DPVBi and CBP:(F–BT)$_2$Ir(acac)/Bphen in BY device, and at the interfaces of NPB/DPVBi, CBP/CBP:Ir(ppy)$_3$, and CBP:CBP:Ir(piq)$_2$(acac)/Bphen in RGB device. The refractive index data for metals were taken from the literature [30]. The optical constants of the organic materials and light outcoupling layers were measured using a variable angle spectroscopic ellipsometer [31].

3.1. Metal–metal microcavity TEWOLED

3.1.1. Influence of different metals on the performance of TEWOLED

The calculations have been performed for six metals (Ag, Au, Al, Mo, Cu and Sm) in BY devices. Ag, Au, Al, Mo and Cu were considered for the bottom anode, and LiF/Al (1 nm)/Ag (15 nm), LiF/Al (1 nm)/Au (15 nm) and Sm (30 nm) were considered for the top cathode. Fig. 1 shows the calculated spectra of the BY devices with different anodes and LiF/Al/Ag cathode in a forward direction.