Extended Abstracts of the 2009 International Conference on Solid State Devices and Materials, Sendai, 2009, pp1180-1181

High Efficiency Top-Emission Organic Light-Emitting Diodes

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1. Introduction

Organic light-emitting devices (OLEDs) have been studied extensively in past twenty years due to its potential applications on display and solid-state lighting [1-2]. Bottom emission is a general design for conventional OLED using transparent conducting film as the anode. However, bottom emission is not appropriate to be applied for the active-matrix displays, which require complicated drive-circuit within limited emission area. Top emission concept is therefore proposed [3-4].

In this work, a high efficiency top-emission OLED (TOLED) with green-light emission is demonstrated. Approaches to improve the efficiency are also investigated, including the anode modification, hole-blocking layer, and capping layer designs onto the semi-transparent cathode.

2. Experimental

A 200 nm-thick silver (Ag) film was deposited on a glass substrate as the device anode. The glass substrate was treated by using the O_2 plasma in advance to improve the adhesion. Then, Ag anode is exposed by the UV-ozone from 1 to 5 minutes to from a thin oxide (AgO_x) layer, such that to enhance the injection of hole carrier [5]. Organic thin films were deposited by using the high-vacuum thermo equipment under a background pressure of 3×10^{-6} Torr.. The schematic structure and corresponding energy-band diagram of the present device are shown in Fig. 1. 4,4',4"-tris(3-methylphenyl henylamino) triphenylamine (m-MTDATA) of 30 nm thickness and *N*,*N'*diphenyl-*N*,*N'*-bis-1-naphthyl)-1,1'-biphenyl-4,4'-diamine (NPB) of 20 nm thickness are used as the hole-injecting layer and hole-transporting layer, respectively. A 45 nm thick emission layer consists of tris-(8-hydroxyquinoline) aluminum (Alq_3) as host and 2,3,6,7-Tetrahydro-1,1,7,7,-tetramethyl-1H,5H,11H-10-(2-benzothiazolyl) quinolizino-[9,9a,1gh]coumarin (C545T) of 1% as the green dopant. 2,9-dimethyl-4,7-diphenyl- 1,10-phenanthroline (BCP) and 2,2',2"-(1,3,5-benzinetriyl)-is(1-phenyl1-H-benzimidazole) (TPBi) is used as the hole-blocking layer, owing to its large highest occupied molecular orbital (HOMO), and the varied thicknesses are 0, 2, and 5 nm. Alq_3 of 3 nm thickness is used as the electron-transporting layer. Lithium fluoride (LiF) of 1 nm thickness was then formed to facilitate the injection of electron carrier from cathode. For a top-emission design, thin Ag layer with 20 nm thickness is used as the semi-transparent cathode of the device.

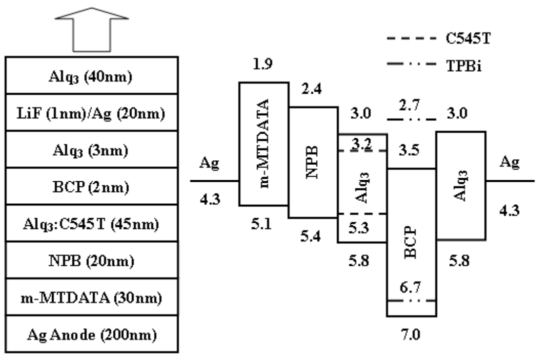

Fig. 1 Schematic structure and corresponding energy-band diagram of the studied top-emission green OLED.

3. Results and Discussions

Metal anode with high reflective index is an important consideration for top emission device design. Various metal anodes have been studied, and silver (Ag) is the most popular due to its high reflectivity for visible light [5]. However, Ag is not an ideal hole-injecting anode, owing to the mismatch of energy level with organic hole-transporting layer. Modifications to increase the work function of Ag anode have been studied [5-6]. Figure 2(a) shows the current density-voltage-luminescence (J-V-L) characteristics of studied devices for UV-ozone exposure time of 1, 4, and 5 minutes, respectively. Device performance is improved obviously when the exposure time increases to 4 minute, and the highest brightness is 12100 cd/m^2. However, device performance degrades when the exposure time increases to 5 minute. In particular, the J-V property of device treated for 5 minute is better than device treated by 1 minute, but the current efficiency of 1.21 cd/A treating for 5 minute is inferior to 2.13 cd/A treating for 5 minute 1 minute. The reduction may be possibly attributed to the deteriorated reflectivity of anode, due to over exposure time.

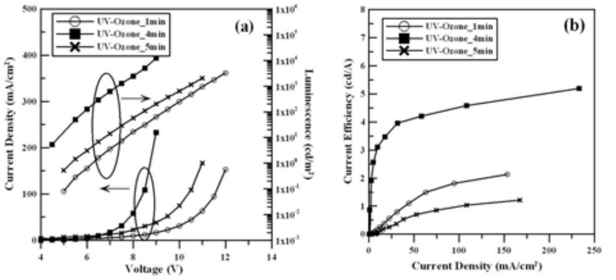

Fig. 2 Characteristics of devices with/without UV-ozone treatment: (a) J-V-L; (b) current efficiency.

To further enhance the carrier recombination in the emission layer, some materials such as BCP and TPBi, which have large HOMO, are used to retard the hole transporting. However, some researches reported the device resistance is increased when using the hole-blocking layer and therefore limited the device efficiency. According to the J-V-L curve shown in Fig. 3(a), J-V characteristic does not change obviously when using 2 nm thick BCP as the hole-blocking layer, but the brightness increases from 3920 cd/m^2 to 61380 cd/m^2. The apparent improvement of brightness produces very high current efficiency of 19.4 cd/A, as shown in Fig. 3(b). However, the brightness decreases to 13980 cd/m^2 when the thickness of BCP increases to 5 nm due to the degraded J-V property. The current efficiency is also reduced to 12.3 cd/A. The results indicate that the hole-blocking layer may increase the device resistance. Therefore, the thickness of the hole-blocking layer has to been optimized.

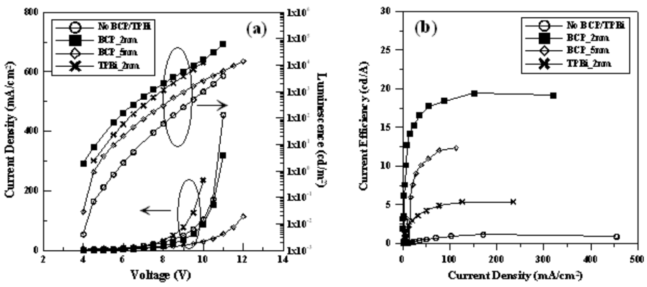

Fig. 3 Characteristics of devices with/without hole-blocking layer: (a) J-V-L; (b) current efficiency.

To increase the light-outcoupling of the device, some researches proposed to deposit a capping layer with high refractive index on the semi-transparent cathode [7]. However, the brightness and efficiency are not obviously improved. The efficiency is only increased slightly from 19.4 cd/A to 20.6 cd/A, but its brightness is decreased by 900 cd/m^2. The electroluminescence (EL) spectra are shown in Figs. 4(a) and 4(b), indicating that the thickness of BCP will influence the color purity of the green OLEDs. It is due to the microcavity effect, and peak positions shift to long-wavelength region with the increasing BCP thickness. It is also found that the EL spectrum was broadened after adding Alq_3 capping layer on the semi-transparent cathode and possibly due to the optical refraction.

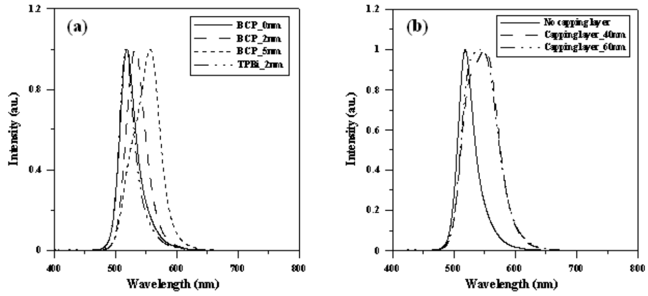

Fig. 4 EL spectra of study TOLEDs: (a) with/without hole-blocking layer; (b) with/without capping layer.

4. Conclusion

In summary, high-efficiency characteristics of green OLEDs with top-emission design have been comprehensively investigated in this work. Two approaches to improve the device efficiency are demonstrated, including modification of the anode electrode to enhance the hole-injecting to the organic layer, and the use of a hole-blocking layer to enhance carrier recombination in the emission layer. In addition, microcavity effect in TOLEDs is diminished after using the organic capping layer of Alq_3. Further investigation on optimize the device performance are currently studied.

Acknowledgements

This work was supported by the Advanced Optoelectronic Technology Center, National Cheng Kung University, under projects from the Ministry of Education and the National Science Council (NSC 94-218-M-008-009) of Taiwan.

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