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Fabrication of blue top-emitting organic light-emitting devices with highly saturated color ☆

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Abstract

Blue top-emitting organic light-emitting devices (TOLEDs) with highly saturated color were developed by microcavity effect. The device structure studied was glass/reflective silver/indium-tin oxide (ITO)/organic electroluminescent stack/semi-transparent cathode (calcium/silver). By changing the thicknesses of ITO and organic layers in the microcavity structure device doped with *p*-bis(*p*-*N*, *N*-di-phenyl-aminostyryl)benzene (DSA-ph), highly saturated color with Commission Internationale de L'Eclairage chromaticity coordinates ($CIE_{x,y}$) of (0.14, 0.08) was obtained.

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Keywords: TOLEDs; Top-emission; Saturated color; Microcavity; Semi-transparent cathode

1. Introduction

Organic light-emitting devices (OLEDs) researches are of great interest because of their application to flat panel displays. Important issues for full color display have been focused on the improvement of emission efficiency, color purity and device stability. The color purity and saturation of each RGB subpixel are critical, in order to meet the requirements of a properly balanced white emission of a full color display. Compared with red and green OLEDs, the efficiency and color saturation of blue devices still need to be improved. It is more difficult to generate deep blue emission due to the intrinsic characteristic of having a wide bandgap. High color purity is also not easy to achieve for most known organic luminescent materials because they tend to have broad EL peak with large full width at half maxima (FWHM) about 70–100 nm, which often leads to reduction of color saturation. Device structure modification can only improve efficiency and color purity of the device slightly. Otherwise, new organic materials may need to be designed and synthesized to alleviate the problem.

For full color active matrix with thin-film transistors (TFTs) drivers [1,2], top-emission structure is known to have large aperture ratio of each pixel and the same time color saturation has also to be considered. The reason is that with increasing saturation of each subpixel of primary RGB emissions, the total power consumption for white light for a given luminance can be reduced [3].

In this work, we demonstrate color-tunable top-emitting organic light-emitting devices by microcavity effect [4–7]. Simply by changing the thickness of ITO in microcavity structure device, more than 150 nm shift of peak emission and less than 40 nm narrow FWHM of electroluminance spectra (EL) can be observed in aluminum tris(8-hydroxyquinoline) (Alq_3) based devices. In addition, the blue DSA-ph doped devices to achieve higher efficiency and color purity is also described.

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2. Experimental

In our experiments, the general structure of top-emitting OLEDs is shown in Fig. 1, where 100 nm thick silver was deposited by thermal evaporation onto a clean glass substrate as reflective layer and following ITO thin film was deposited by 300 W RF sputtering as anode. In addition, copper phthalocyanine (CuPc) and 4,4′-bis [*N*-(1-naphthyl)-*N*-phenyl-amino]biphenyl (NPB) were adopted as the hole injection layer (HIL) and hole-transporting layer (HTL) respectively. 2-(*t*-butyl) di-(2-naphthyl)anthracene (TBADN) [8] was used as the host for blue dopants in emitting layer (EML) and Alq_3 was served as the electron-transporting material. These organic materials were deposited by thermal evaporation in an ULVAC Solciet OLED coater at a base vacuum of 10^{-7} Torr. Semi-transparent cathode of calcium and silver thin films were fabricated similarly in the separate chamber. Electroluminescent (EL) spectra, luminance yield and $CIE_{x,y}$ color coordinates were measured by a Photo Research PR-650 spectrophotometer driven by a programmable dc source.

3. Result and discussion

3.1. Microcavity model in OLEDs

The principal of microcavity can be realized by the spontaneous emission that resonates in a cavity composed of the total reflective mirror and semi-transparent thin film, from which only certain wavelength is allowed in cavity modes, and emits light in a given direction. Intensity enhancement and spectra narrowing are the most common phenomena caused by microcavity effect.

In our devices, the reflective mirror is contributed by the 100 nm thick silver with more than 80% reflectivity throughout the visible region. Semi-transparent cathode is the combination of two layers of calcium and silver with proper thickness. In literature [4], optical length of the cavity is given by

$$L = \frac{\lambda}{2}\left(\frac{n}{\Delta n}\right) + \sum_i n_i L_i + \left|\frac{\phi_m}{4\pi}\lambda\right|, \quad (1)$$

where λ is the free-space wavelength, n_i and L_i are the reflective index and thickness of ITO and organic layer. The contribution of optical length is more obvious in different thickness of ITO because of larger reflective index ($n = 2.2$) than that of organic layer ($n = 1.6$–1.7). By changing the optical length of the device, we can tune the emissive color systematically.

3.2. Oxygen plasma pretreatment

Before organic materials were coated onto the substrate, Ag/ITO glass substrates were treated with 200 W oxygen plasma. Atomic force microscope (AFM) images of Ag, pristine Ag/ITO and Ag/ITO after oxygen plasma treatment are shown as Fig. 2. The surface roughness (Rms) of these three are 1.252, 1.221 and 0.908 nm, respectively. This result shows that all substrates were found to be smooth and the substrates after oxygen plasma treatment are with better morphology.

3.3. Alq_3 based devices

Devices with configuration of Ag (100 nm)/ITO/CuPc (15 nm)/NPB (60 nm)/Alq_3 (75 nm)/Ca (20 nm)/Ag (15 nm) were fabricated. With variation of ITO thickness from 50 to 150 nm, dramatic differences in EL spectra and device performance are observed as depicted in Fig. 3. Different emissive colors from bluish green to orange can be obtained from the microcavity devices with a single Alq_3 emitter.

When the thickness of ITO is 50 nm, the EL of Alq_3 peaks at 500 nm and its full width at half maxima (FWHM) was narrowed to only 36 nm. The luminance yield of 3.3 cd/A was achieved as the ITO thickness was increased to 75 nm, and the EL peak shifts to 516 nm without changing the FWHM. The red shift was continued when ITO increased to 100, 125 and 150 nm with the EL peaks appeared near 572, 608 and 664 nm respectively. The Alq_3 device with best luminance yield of 4.5 cd/A was achieved when the thickness of ITO reaches 100 nm.

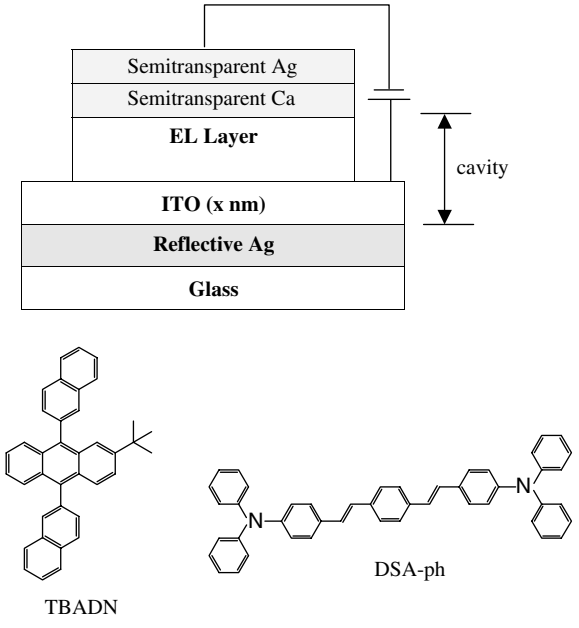

Fig. 1. The device structure of the TOLED.

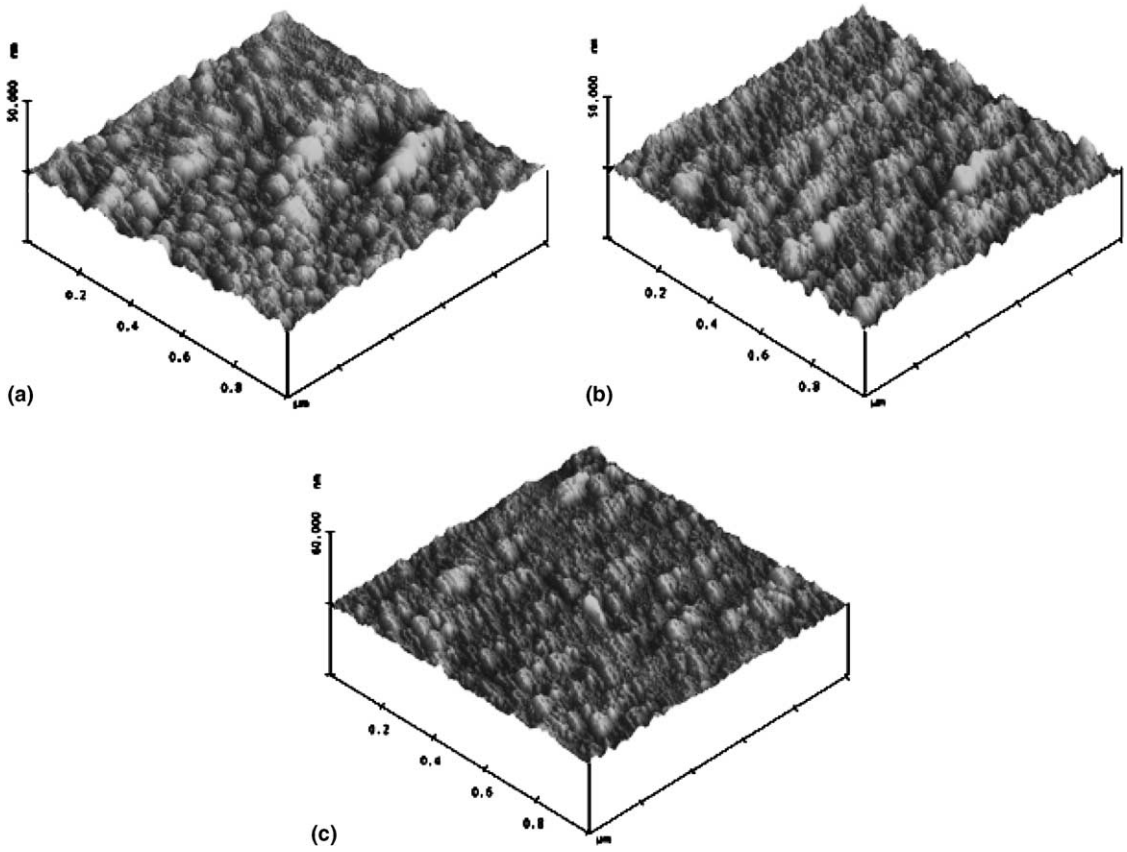

Fig. 2. The AFM image of (a) Ag 100 nm, (b) pristine Ag 100 nm/ITO 100 nm, and (c) Ag/ITO with oxygen plasma treatment.

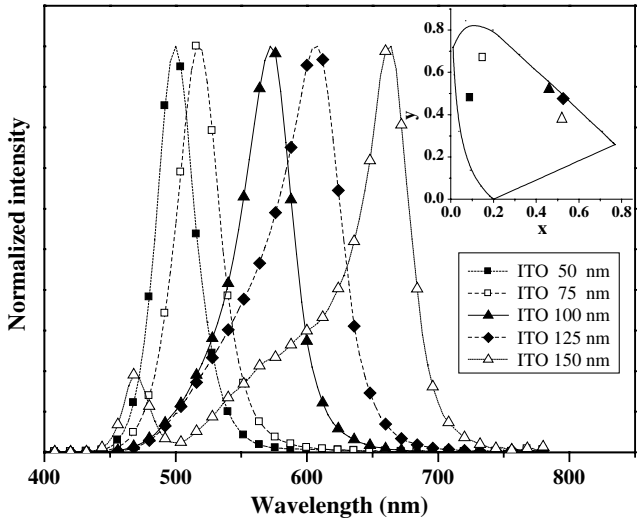

Fig. 3. Normalized Alq_3 EL spectra and 1931 $CIE_{x,y}$ coordinates of TOLEDs with five different thickness of ITO in the Ag/ITO anode.

These results can be rationalized by microcavity effect as by tuning the thickness of ITO, the EL spectrum maxima is shifted in a wide range (from 500 to 664 nm) and the shape of the EL spectrum is also changed. The corresponding color change of this Alq_3 based TOLED in term of $CIE_{x,y}$ is shown in the inset of Fig. 3.

3.4. Blue DSA-ph devices

3.4.1. Microcavity optimization of ITO thickness

The same phenomena also can be observed in DSA-ph doped device structure of Ag (100 nm)/ITO/CuPc (15 nm)/NPB (40 nm)/5% DSA-ph in TBADN (20 nm)/Alq_3 (20 nm)/Ca (20 nm)/Ag (15 nm). As the ITO thickness (i.e. optical length of the device) increases, large red shift (from 464 to 532 nm) of the EL peaks are observed as in Fig. 4. EL performance of the device with different thickness of ITO is also shown in Table 1. With 75 nm thick ITO, highly saturated color was achieved with $CIE_{x,y}$ (0.14, 0.08) and luminance yield is 0.9 cd/A. Although higher efficiency (3.0 cd/A) of blue device can be fabricated with increased thickness of ITO (100 nm), the color is shifted to bluish green with $CIE_{x,y}$ (0.12, 0.37). While the CIE color coordinate of the DSA-ph bottom-emitting device is (0.17, 0.36). Contrary to the bottom-emitting devices, we found the TOLEDs doped with DSA-ph show sharper emissions at 464 nm with FWHM of only 28 nm. The emissive color of the doped TOLEDs is purer and more saturated than that of the bottom-emitting ones.

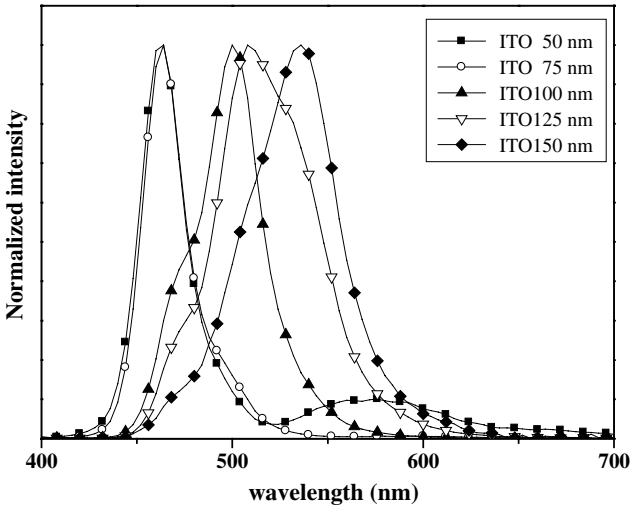

Fig. 4. Normalized DSA-ph EL spectra with five different thickness of ITO in the Ag/ITO anode.

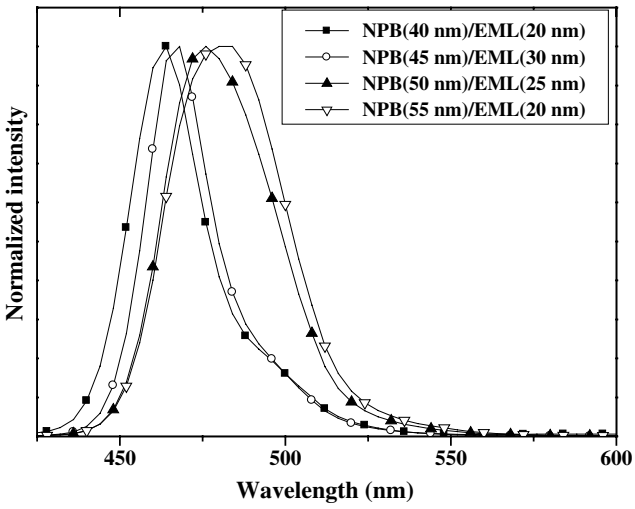

Fig. 5. Normalized DSA-ph EL spectra with different thickness of organic layer.

Table 1
EL performance of different ITO thickness blue devices

Thickness of ITO (nm)	Yield (cd/A)	CIE_x	CIE_y	λ_{max} (nm)	FWHM (nm)
50	0.1	0.19	0.14	464	28
75	0.9	0.14	0.08	464	28
100	3.1	0.12	0.37	500	52
125	2.3	0.18	0.54	508	56
150	2.8	0.19	0.59	532	64

3.4.2. Microcavity optimization of organic layers

As Eq. (1) describes, both ITO and organic layer affect the optical length of the device. Because of larger reflective index of ITO than that of organic layer, obvious EL peak shift can be observed. In this section, we fixed ITO thickness and try to modify organic layer thickness to enhance the luminance yield.

Table 2 shows EL performance of the DSA-ph devices, Ag (100 nm)/ITO (75 nm)/CuPc (15 nm)/NPB/5% DSA-ph in TBADN/Alq_3 (20 nm)/Ca (20 nm)/Ag (15 nm), depending on the thickness of HTL (NPB) and EML (DSA-ph in TBADN). EL spectra are shown in Fig. 5. With increasing thickness of organic layer, slight red shift is observed as expected.

Table 2
EL performance of blue TOLEDs with different NPB and EML thickness

NPB/ EML	Yield (cd/A)	CIE_x	CIE_y	λ_{max} (nm)	FWHM (nm)
40/20	0.9	0.14	0.08	464	28
45/30	1.0	0.13	0.09	468	20
50/25	1.4	0.10	0.20	476	40
55/20	2.1	0.10	0.20	480	40

4. Conclusions

We demonstrated highly saturated blue top-emitting OLEDs with $CIE_{x,y}$(0.14, 0.08), which is comparable to NTSC standard. By tuning optical length in the microcavity adjusted structure and the judicious choice of fluorescent dopants, highly pure and saturated color of OLEDs can be carried out.

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