Spectrum study of top-emitting organic light-emitting devices with micro-cavity structure*

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Abstract: Blue and white top-emitting organic light-emitting devices OLEDs with cavity effect have been fabricated. TBADN:3%DSAPh and Alq_3:DCJTB/TBADN:TBPe/Alq_3:C545 were used as emitting materials of microcavity OLEDs. On a patterned glass substrate, silver was deposited as reflective anode, and copper phthalocyanine (CuPc) layer as HIL and 4'-bis[N-(1-Naphthyl)- N-phenyl-amino]biphenyl (NPB) layer as HTL were made. Al/Ag thin films were made as semi-transparent cathode with a transmittance of about 30%. By changing the thickness of indium tin oxide ITO, deep blue with Commission Internationale de L'Eclairage chromaticity coordinates (CIEx,y) of (0.141, 0.049) was obtained on TBADN:3%DSAPh devices, and different color（red, blue and green）was obtained on Alq_3:DCJTB/TBADN:TBPe/Alq_3:C545 devices, full width at half maxima (FWHM) was only 17 nm. The spectral intensity and FWHM of emission in cavity devices have also been studied.

Key words: microcavity; top-emitting; semi-transparent cathode
DOI: 10.1088/1674-4926/30/4/044007 **EEACC:** 4260D

1. Introduction

Brightness and efficiency are crucial factors for display or lighting applications based on organic light-emitting devices (OLEDs). The microcavity structure can improve the optical structure of the device, and often important increases can be obtained without changing the fundamental electronic or physical principles of the device**.** One of the characteristics of both photoluminescence and electroluminescence in organic materials is their large spectral line width[1], frequently greater than 70 nm. This occurs in both small molecules such as Alq_3[2] and conjugated polymers. Since the cavity enhances the emission rate at the resonance wavelengths of the cavity and suppresses the emission rate at other wavelengths[3,4], the spontaneous emission rate and the emission spectrum of an optical emitter can be modified. The top-emission structure has large aperture ratio of each pixel for full color active matrix with thin-film transistor (TFT) drivers[5−7]. In this work, top-emitting organic light-emitting devices with microcavity effect were made. By changing the thickness of indium tin oxide (ITO), the color of the devices can be changed and at a particular thickness the devices can achieve higher saturated color.

2. Experiment and theory

In this work, we reported the fabrication and characterization of the TBADN:3%DSAPh based microcavity OLEDs emitting in the optical spectral region. The device structure and materials used are shown in Figs. 1 and 2. The device consists of Ag/ITO/CuPc /NPB/TBADN:3%DSAPh/Alq_3/LiF/Al(Ag) as shown in Fig. 1, where Al/Ag layer acts as a semitransparent surface. On a patterned ITO electrode, we made copper phthalocyanine (CuPc) layer for HIL, 2-(t-butyl)di-(2-naphthyl) anthracene(TBADN) for EML, 4'-bis[N- (1-Naphthyl)-N-phenyl-amino] biphenyl(NPB) layer for HTL. The total thickness of organic layers is about 100 nm. ITO thin film was deposited by 200 W magnetron sputtering as anode. Silver was deposited by 250 W RF sputtering as reflecting layer and Alq_3 was served as the electron-transporting material. Organic materials were deposited by thermal evaporation at a base vacuum of 10^{-6} Torr.

Microcavity determines the electric-field mode distribution, thereby modifying the exciton spontaneous emission lifetime and hence the quantum efficiency. This, in turn, can modify the spectral width[8] and distribution of the emission intensity[9]. In a microcavity device, the total optical thickness

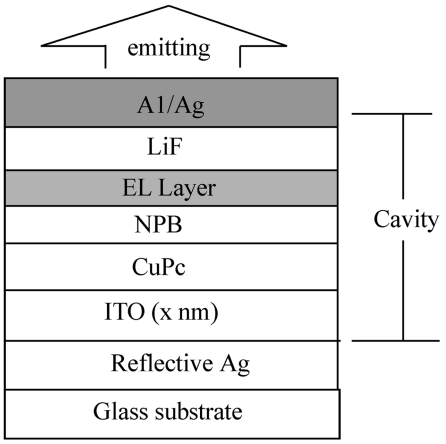

Fig. 1. Schematic structure of the microcavity OLED.

* Project supported by the National Natural Science Foundation of China (No. 60477014).
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Received 4 September 2008, revised manuscript received 3 November 2008

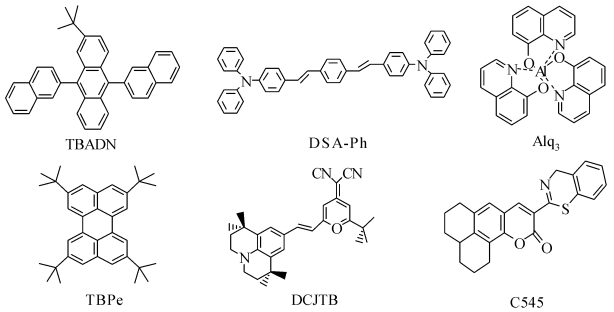

Fig. 2. Materials of the microcavity device.

L of the cavity is given by Eq. (1). In this equation, λ is the free-space wavelength, n_{eff} is the effective refractive index of the quarter wave stack, n_{i} and L_{i} are filler layer indices and thicknesses, Δn is the index difference between the materials that constitute the quarter wave stack and Φ_{m} is the phase shift at the metal reflector:

$$L = \frac{\lambda}{2}\frac{n_{\text{eff}}}{\Delta n} + \sum_{\text{i}} n_{\text{i}} L_{\text{i}} + \left|\frac{\phi_{\text{m}}}{4\pi}\lambda\right|. \tag{1}$$

The first term in Eq. (1) is due to the effective penetration depth in the distributed Bragg mirror of quarter wave stack and the second term is the sum of the optical thicknesses of the layers in the device. The last term in Eq. (1) is usually small in comparison to the other two with the phase shift ϕ_{m} being given by Eq. (2). In this equation, n is the refractive index of the organic contact with the metal, and n_{m} and k_{m}, are the real and imaginary parts of the metal refractive index:

$$\phi_{\text{m}} = \arctan\left(\frac{2n_{\text{i}}k_{\text{m}}}{n_{\text{s}}^2 - n_{\text{m}}^2 - k_{\text{m}}^2}\right). \tag{2}$$

It is possible to change the total optical thickness and the spectral position of the electromagnetic cavity modes by changing the thickness of the filler layer.

In optically pumped organic microcavity structures with reflective mirrors, lasing action has been observed[10]. However, even weak reflections in a conventional OLED structure are sufficient to form a microcavity that can significantly influence device luminescence properties[11]. The classical treatment using wave optics and a transfer matrix formalism at the dielectric boundaries was shown to agree with measured changes in the emission intensity with layer thickness[12] and spectral narrowing in microcavity structures. Classical wave optics applied to a Fabry-Perot etalon was also shown to describe spatial variations in the emission intensity[13] and spectrum[14].

Semi-transparent cathode is an important factor of microcavity structure for organic light-emitting diodes. We made aluminum and silver thin films as semi-transparent cathode.

3. Result and discussion

Figure 3 is the spectrogram of devices made with Ag/ITO/CuPc/NPB/TBADN:3%DSAPh/Alq_3/LiF/Al(Ag) structure. The emission spectra were measured, the detection

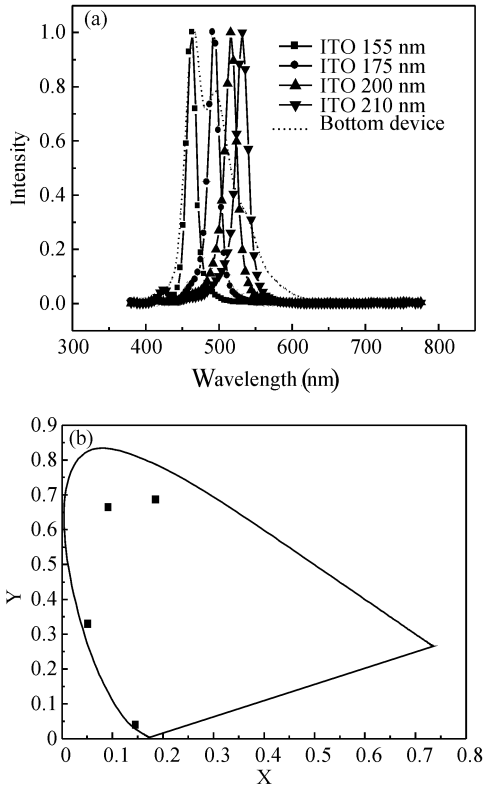

Fig. 3. (a) TBADN:DSAPh EL spectra with four different thicknesses of ITO (the dotted line represents EL spectra of bottom emitting device) and (b) CIEx, y coordinates with four different thicknesses of ITO.

angle θ was taken to be zero at normal incidence, and the emission intensity at different emission angles were not been studied in this paper.

Semi-transparent cathode is an important factor of microcavity structure for organic light-emitting diodes. We made aluminum and silver thin films as semi-transparent cathode. The transmittance of aluminum and silver (Al/Ag) thin films cathode was about 30%. The ITO anodes with a nominal sheet resistance of 30 Ω/square were cleaned using detergent and then were treated by UV ozone before coated with organic materials. The ITO surface found to be smoother and more orderable after treating by UV ozone.

As the thickness of ITO increases, the length of cavity also increases. Figure 3 is the spectrogram of different thicknesses of ITO. Compared to the devices without cavity structure (bottom devices), the full width at half maxima (FWHM) became narrowed. When the ITO thickness increases from 155 to 210 nm, dramatic differences in EL spectra and device performance are observed as depicted in Fig. 3. Different emissive colors from blue to green can be obtained from the microcavity devices with a TBADN:3%DSAPh emitter layer.

When the ITO thickness was 155 nm, the EL of TBADN:3%DSAPh peaks at 464 nm and its FWHM was only 17 nm. When the ITO thickness increased to 175, 200 and 210 nm with the EL peaks appeared near 492, 516 and 532 nm, the FWHM were 18, 20 and 21 nm respectively (Table 1).

Deep blue color was achieved with CIEx, y, (0.141, 0.049) (Fig. 3) of blue device. When it was fabricated with

Table 1. EL performance of different devices.

Thickness of ITO (nm)	Yield (Cd/A)	CIEx	CIEy	λ_{MAX} (nm)	FWHM (nm)
155	0.32	0.141	0.049	464	17
175	0.79	0.069	0.321	492	18
200	0.858	0.092	0.668	516	20
210	0.832	0.175	0.682	532	21

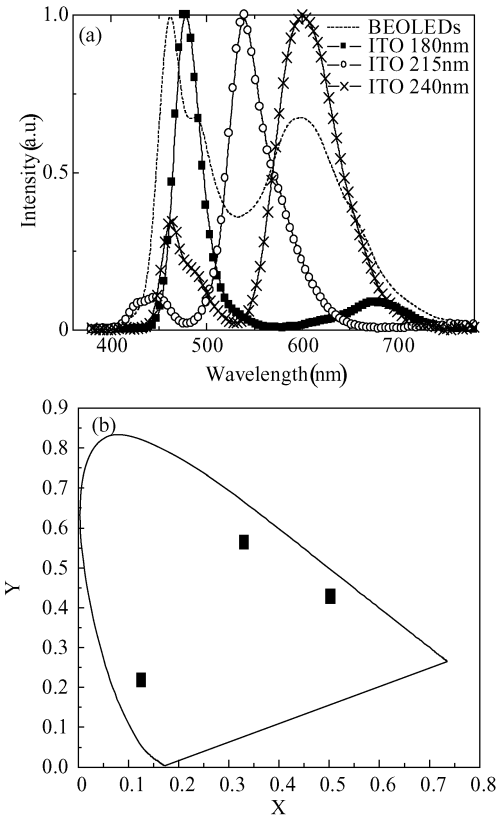

Fig. 4. (a) "Alq3:DCJTB/TBADN:TBPe/Alq3:C545" device EL spectra with four different thicknesses of ITO (and the dotted line represents EL spectra of bottom emitting device) and (b) CIEx, y coordinates with four different thicknesses of ITO.

increased thickness of ITO, the color was shifted to bluish green with CIEx, y (0.092, 0.668). While the CIE color coordinates 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 showed sharper emissions at 464 nm with FWHM only at 17 nm. The emissive color of the doped TOLEDs was purer and more saturated than that of the bottom-emitting ones. It is indicated that employing the microcavity structure in TOLED is a promising route to achieving pure-blue emission.

Figure 4 is the spectrogram of different thicknesses of ITO, Devices made with Ag/ITO/CuPc/NPB/Alq_3:DCJTB/TBADN:TBPe/Alq_3:C545/LiF/Al(Ag) structure. Compared to the devices without cavity structure, the FWHM became narrowed. When the ITO thickness increased from 180 to 240 nm, differences device performance are observed as depicted in Fig. 4. Different emissive colors from blue to red can be obtained from the microcavity devices with "Alq_3:DCJTB/TBADN:TBPe/Alq_3:C545" emitter layer.

Table 2. EL performance of devices.

Thickness of ITO (nm)	Yield (Cd/A)	CIEx	CIEy	λ_{MAX} (nm)	FWHM (nm)
180	0.263	0.133	0.201	475	30
215	0.503	0.335	0.567	538	48
240	0.284	0.513	0.413	603	70

When the ITO thickness was 180 nm, the EL of device peaks at 475 nm and its FWHM was only 30 nm. When the ITO thickness increased to 215, 240 nm with the EL peaks appeared near 538 and 603 nm, the FWHM were 48 and 70 nm respectively. The color of Alq_3:DCJTB/TBADN:TBPe/Alq_3:C545 bottom is white, but through the effect of cavity structure, the color is changed to blue and red. As the ITO thickness increases, the FWHM of the device also increases (Table 2).

The luminance yield of 0.503 CD/A was achieved as the ITO thickness was increased to 215 nm, and the EL peak shifts to 536 nm with 48 nm of the FWHM. The red shift was continued when ITO increased to 240 nm with the EL peaks appeared near 603 nm. By changing the thickness of ITO, different color was obtained on devices. We obtained the CIE coordinates of (x = 0.513, y = 0.413), (x = 0.133, y = 0.201) and (x = 0.335, y = 0.567), FWHMs of 70, 30 and 48 nm for red, blue and green, respectively.

4. Conclusion

In conclusion, we fabricated deep blue top-emitting OLED with the semitransparent cathode (Al/Ag film) of about 30%. The blue and white top-emitting organic light-emitting devices with cavity effect were fabricated. TBADN: 3%DSAPh and Alq_3:DCJTB/TBADN:TBPe/Alq_3 : C545 have been used as emitting materials for microcavity OLEDs. By changing the thickness of ITO, different colors were obtained with Alq_3:DCJTB/TBADN: TBPe/Alq_3:C545 based devices. When the thickness of ITO was 155 nm, TBADN:3%DSAPh based TOLED exhibited a narrowed EL peak at 464 nm and (CIEx, y) of (0.141, 0.049).

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