P-78: Design and Characterization of Organic Light Emitting Diodes with Microcavity Structure

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Abstract

An organic light emitting diode with a microcavity structure has been fabricated. The intensity enhancement at the resonance wavelength is 2.3 compared to a non-cavity device. The emission color is also modified from a yellow-green of non-cavity device to a primary green for the microcavity device. The experimental results compared well to theoretically calculations.

1. Introduction

Organic light emitting diodes (OLEDs) are challenging liquid crystal displays (LCDs) as one of the most promising next-generation flat-panel displays because of their ease of manufacturing, all solid state design, faster switching speed and being self-emitting with wider viewing angle [1].

The basic structure of the OLED consists of a pair of electrodes and multilayers of organic materials. Due to their intrinsic characteristics, emission spectra of many OLEDs are rather broad, with FWHM usually around 100nm. Thus the emissions from OLEDs have unsaturated colors. Tokito *et al* reported that using a microcavity structure, strongly directed pure RGB colors were emitted from OLEDs [2]. Several research groups also reported the spectral narrowing and intensity enhancement of spontaneous emission occurred in the microcavity OLEDs [3-5]. However, in their reports the angle dependence of emission spectrum were not discussed in detail. This angular dependence is actually very severe, which is not desirable for display application. In this article, we describe an OLED with a microcavity design for purifying the emission color. Pure green color is observed within an angle of 40° relative to the normal direction. Meanwhile, intensity enhancement at the resonance wavelength is demonstrated in the microcavity device as well. The design, fabrication, and EL characteristics of the devices will be discussed.

2. Microcavity LED design and fabrication

2.1 Microcavity design

The schematic structure of a microcavity OLED is shown in Fig. 1(a). The bottom mirror is composed of a dielectric distributed Bragg reflector (DBR). The DBR consists of periodic structure of two materials with large index difference, which offers tunable reflectivity over a certain wavelength region. The total optical thickness of the cavity, is given by:

$$L(\lambda) = L_{DBR} + \sum_i n_i L_i + L_m \,. \qquad (1)$$

The first term in eq. (1) is the penetration depth of the electromagnetic field into the dielectric stack. The second term is the sum of optical thickness of the organic materials and ITO

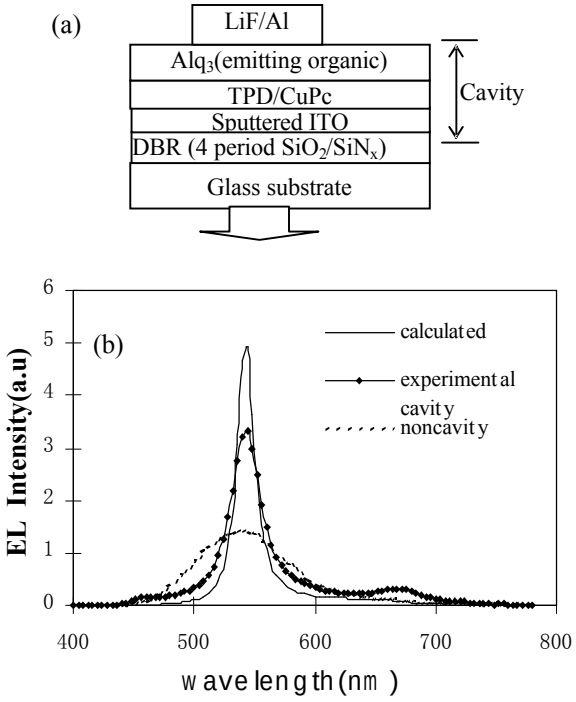

Figure 1. (a) the structure of the microcavity organic light emitting diodes (b) the normal direction electroluminescent spectra of devices with and without microcavity structure.

between two mirrors, and the last term is the effective penetration depth into the metal mirror, which can be calculated according to the Fresnel reflection formula. Usually, the total thickness of the organic materials in OLED structure is about 100 nm and the ITO thickness is determined by considering good electrical conductance and high transparence. Therefore, the optical length of the cavity can be modified by varying the first term in eq. (1), which depends on the index difference between the layers that constitute the stack as well as the number of the periodic layers. And the modification will result in different emission using the same emissive organic material.

The theoretical spectrum for emission normal to the plane of the devices layers was calculated following the approach of Deppe *et al* [6]. The calculated spectrum compared with that of noncavity structure is:

$$\frac{|E_m(\lambda)|^2}{|E_{nc}(\lambda)|^2} = \frac{\dfrac{1-R_{DBR}}{j}\displaystyle\sum_j \left[1 + R_m + 2\sqrt{R_{DBR}}\cos\left(\frac{4\pi x_j}{\lambda}\right)\right]}{1 + R_m R_{DBR} - 2\sqrt{R_m R_{DBR}}\cos(4\pi L/\lambda)} \qquad (2)$$

 ISSN/0003-0966X/03/3401-0516-$1.00+.00

where R_m and R_{DBR} are the reflectivities of the metal and DBR mirrors, respectively, L is the total optical thickness of the cavity given in Eq (1), $|E_{nc}(\lambda)|^2$ is the free space mission intensity, and x_j are the effective distance of the emitting dipoles from the metal mirror. The resonance modes are determined by the relation $m\lambda=2L(\lambda)$, where m is the mode index. By modifying the optical length, the mode positions and mode spacing can be varied.

2.2 Microcavity OLED fabrication

The fabrication of microcavity OLED started from formation of the DBR. In our experiment, the DBR consisted of four pairs of SiN_x and SiO_2, which were deposited by plasma-enhanced chemical vapor deposition (PECVD) on a glass substrate at 300°C. The DBR acted as a bottom partially reflecting mirror through which the light was emitted. For comparison, a control sample with bare glass was also prepared. An ITO layer was deposited on top of the DBR and the control glass substrate as an anode using a DC sputtering system. The ITO thickness was 100nm. After solvent cleaning and UV O-zone exposure, organic layers with the sequence of CuPc(20nm)/TPD(40nm)/Alq (50nm) were deposited on ITO anode by thermal evaporation under pressure below $2x10^{-6}$torr. A thin layer LiF was deposited on Alq followed by deposition of 150nm Al. Film thickness was determined *in situ* using a crystal monitor. The thickness of the various layers are optimal for this conventional OLED structure [7]. The LiF/Al serves both as cathodes and as the top mirror. The device area is defined to be $2x2mm^2$ using a shadow mask. The optical properties of layered media in the device were measured using spectroscopic ellipsometry.

3. Results and Discussion

The dielectric mirror plays an important role in the design of the microcavity OLED. In the DBR, the thickness of each layer is chose so that the optical length is equal to quarter wavelength of the peak position of the free space emission spectrum. In this study, the electroluminescence of the non-cavity device has a peak value at 540nm. The measured refractive index of SiN_x and SiO_2 at this position are 2.07 and 1.48 respectively. So the thickness of two layers was decided to be 65 nm and 91nm respectively. The reflectivity of the dielectric mirror is calculated using transfer matrix method [8]. The calculated and measured reflectance of the designed DBR is shown in Fig. 2. In a microcavity the emitting light will be modified by the optical mode. As the result, the spectrum will become narrower, and the intensity of the resonance mode will be enhanced.

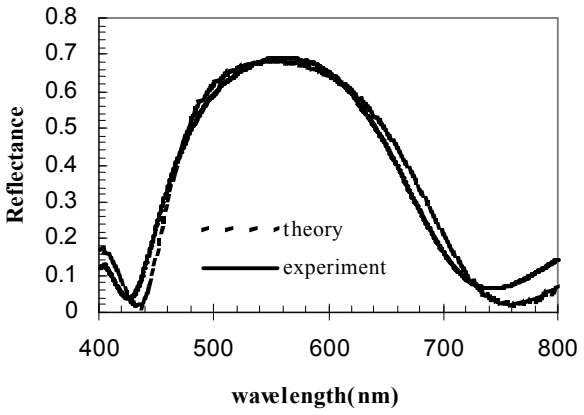

Figure 2. Calculated and measured reflectance of a DBR consisting of four period SiO2/SiNx. At the resonance wavelength(λ=540nm), the reflectivity is 0.68

Figure 1(b) shows the comparison of the EL spectra from normal direction of the microcavity OLED and that without cavity structure. Both spectra are obtained under the current density of $16mA/cm^2$. The theoretical spectra calculated according to the eq. (2) is also shown in the same figure. In our calculation, the emitting dipole is assumed to be distributed in a ~20-nm thick region of Alq3 layer adjacent to the Alq/TPD junction. This assumption is consistent with that reported by Tang [9]. The experimental results and theoretical calculation agree very well except a higher intensity at resonance wavelength from theoretical calculation. We believe the discrepancy is due to self absorption by the organic layer. The spectra of both cavity and non-cavity devices have peaks at the same wavelength of 540nm. The enhancement of the emission intensity along the cavity axis (at the resonance wavelength) is 2.3. Compared with the non-cavity device, the device with a cavity structure has a narrower spectrum with FWHM of 30 nm, which gives a more saturated color.

We also measured the angular dependence of the emission spectrum of both devices. Figure 3 shows those of the cavity device. The resonance wavelength is blue shifted as the angle increases with respect to the normal, and the peak intensity decreases gradually. Meanwhile, another mode at the red region appears and increases with angle. The reason for the angular dependence is because both reflection of the DBR and cavity optical length vary with angles, which leads to the variation of

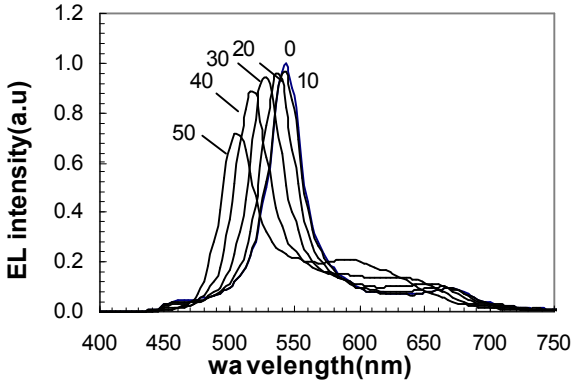

Figure 3. The electroluminescent spectra measured at 0°,10°,20°,30°,40° and 50° from the surface normal of a microcavity organic light emitting diode with normal incidence optical mode located at 540nm.

the resonant wavelength. However, our simulation indicates that if the resonance wavelength is chosen properly within the emission spectrum, the emission color change is not too severe within a viewing cone of 90°. The experimental results show a 20nm shift of the resonance wavelength for an angle of 40°. The corresponding color change is not observable by human eyes.

Figure 4 shows the CIE-1931 color diagram of the emission observed at the each angular position of both microcavity devices and non-cavity devices. The light emission from the non-cavity

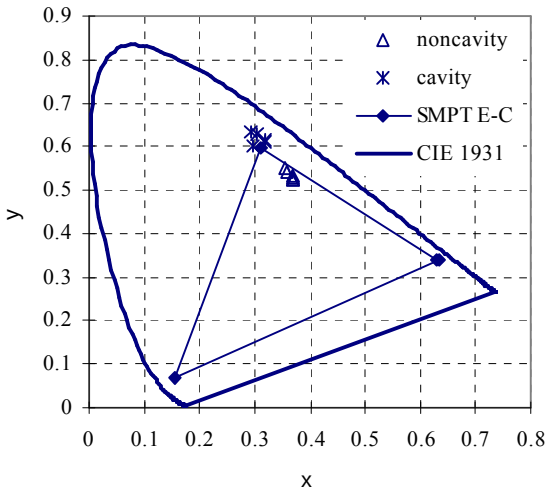

Figure 4. Chromatic values of emission from both a microcavity OLED and a noncavity diode.

device is yellow green according to the color coordinates. The color is also angular-dependent, which is due to the weak microcavity effect of the multiplayer structure. On the other hand, the color of the light from the cavity device is very close to the primary green. Although the pure green color is observed just in 40° relative to normal direction, it is enough for some close-viewing application.

The total intensity enhancement was measured by integrating the radiant power over all solid angles. For measuring the radiant power distribution, the devices were mounted in on a rotational stage located 15 cm from a calibrated photodiode. The entrance pupil was defined by a pinhole with diameter of 2 mm. The distribution of both devices is shown in the Fig. 5. The Lambertian distribution is also plotted as a reference. The non-cavity emission is found to be very close to the Lambertian. The distribution pattern of the cavity device, however, is narrower. In the normal direction, the cavity has integrated enhancement of 1.3.

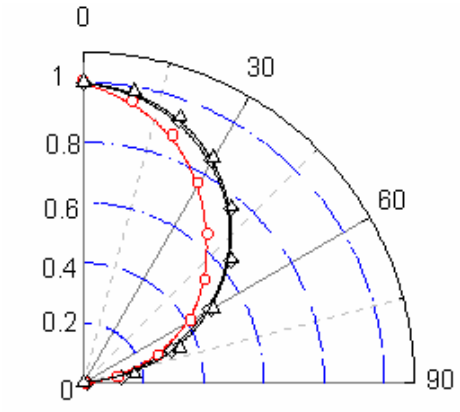

Figure 5. The emission pattern angular distribution of OLED with microcavity (š), noncavity (r), compared with the lambertian distribution(¸)

The total intensity of the cavity device is calculated to be about 0.9 relative to the non-cavity device. The intensity decrease can be explained according to Purcell effect [10]. The active material gain bandwidth (emission spectrum in free space) is greater the cavity resonance bandwidth, so emission at the resonance wavelength is strongly enhanced and emission at other wavelengths suppressed. Consequently, the total intensity enhancement could be less than one. However, it means if the organic material has a narrow free-space emission spectrum, total enhancement can be achieved by using deliberately designed microcavity structure. For example, Jordan *et al* has demonstrated a net efficiency enhancement as high as 1.8 from a microcavity OLED with the free-space emission spectra narrower than 50nm [11].

We note that the free spectrum of the current OLED is in the green region. So the microcavity is designed to narrow the spectrum to obtain pure green light in a wide angle. For red or blue emission material, a similar effect should be achievable by using the microcavity DBR structures with the appropriate thickness and period.

4. Conclusion

In summary, we have demonstrated the fabrication of an organic light emitting diode with a microcavity structure. Theoretical calculation has also been given for the design of cavity. The experimental results shows that the emission spectrum of the Alq based organic light emitting devices can be narrowed markedly, from 100nm to 30nm, resulting in a purified color gamut. And the color change with viewing angle is not observable over an angle of 40^{o} relative to normal direction. The intensity enhancement at the resonance wavelength is 2.3 and the integrated enhancement is 0.9 compared to the non-cavity device. The structure will be optimized to achieve higher integrated intensity enhancement.

5. Acknowledgements

This work was supported by the Research Grants Council of the Hong Kong Special Administrative Region.

6. References

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