Optical Simulation for High Efficiency OLEDs

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Abstract

An optical model based on the optical thin-film theory is derived to calculate the output radiance of small molecules organic light-emitting diodes (OLEDs). We have designed the high efficiency OLEDs using the reflectance phase control of dielectric layers. It is found that OLED with a single TiO_2 dielectric layer is a good candidate to enhance the outcoupling efficiency and increase the color purity.

1. Introduction

Many researches on high efficiency organic light-emitting diodes (OLEDs) have been reported to apply for flat-panel display [1-3]. Especially, aerogel, microlens array, scattering layer, photonic crystal structure and microcavity structure with dielectric layers have been used to enhance the electroluminescence (EL) output intensity [2-7]. In the OLEDs, the output spectrum of EL is affected by the interference effect because the OLED consists of multilayers and the total thickness of the OLED is comparable with the wavelength in visible region [1, 7, 8]. Also, the dipole position in an emitting layer (EML) is an important factor in the interference effect, together with adjustment of organic layer for carrier valance control [9]. The external emission spectrum or radiance as a function of viewing angle can be calculated using the optical thin-film theory [6-11]. However, there are few discussions for optimization of high efficiency OLEDs in the optical point of view.

In this paper, we report that the reflectance phase controlled TiO_2 dielectric layer plays an important role in enhancing the outcoupling efficiency. The EL spectrum and angular radiance of high efficiency OLEDs are numerically simulated by use of the optical model based on the optical thin-film theory. We demonstrate the optical role of dielectric layers between ITO and glass.

2. Optical model of OLEDs

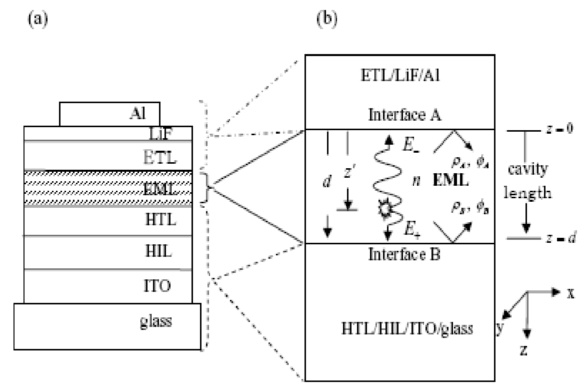

Figure 1. (a) Typical OLEDs architecture, (b) Optical model for the OLEDs structure.

A multilayer thin-film structure of the OLED is shown in Fig. 1(a). Following the optical thin-film theory, the multilayer OLED structure can be simplified as a single layer between two interfaces A and B as shown in Fig. 1(b). The light generated in an EML propagates in upward and downward directions with multiple beam reflections between two interfaces. The output radiance can be calculated using the coherent summation of reflected lights. Then the intensity of radiated EL out of the OLEDs can be derived as follows [11]:

$$I_{ext}(\theta,\lambda,z) = \left[\frac{T_B}{\left(1-\sqrt{R_A R_B}\right)^2} \frac{1}{\left(1+F_{FP}\sin^2\frac{\Delta_{FP}}{2}\right)} \right] \times \left[\left(1+\sqrt{R_A}\right)\left(1+F_{TBI}\cos\Delta_{TBI}\right)\right] \times I_{int}(\theta,\lambda) \qquad (1)$$

where

$$F_{FP} = \frac{4\sqrt{R_A R_B}}{\left(1-\sqrt{R_A R_B}\right)^2}\ , \qquad (2)$$

$$F_{TBI} = \frac{2\sqrt{R_A}}{1+R_A}, \qquad (3)$$

$$\Delta_{total} = \phi_A + \phi_B - \frac{4\pi n_e d}{\lambda}\cos\theta_e, \qquad (4)$$

$$\Delta_{TBI} = \phi_A - \frac{4\pi n_e z'}{\lambda}\cos\theta_e. \qquad (5)$$

In the above equation, R_A, R_B, ϕ_A, and ϕ_B represent the reflectances and the phase changes on reflection at the A and the B interfaces, respectively. n_e and d are the refractive index and the thickness of the EML, respectively. z' and θ_e are the distance from interface A to the dipole and the incident angle of the plane waves at interfaces A and B in the EML, respectively. Incident angle θ_e in EML is related to the viewing angle θ by the Snell's law. $I_{\text{int}}(\theta,\lambda)$ is the spontaneous emission spectrum of the EML in free space.

It is noted that the spectral radiance for OLEDs consists of Fabry-Perot multiple beam interference term in the first bracket, two-beam interference term in the second bracket, and the spontaneous emission spectrum of the EML as shown in Eq. (1) [11]. The maximum intensity of OLEDs can be obtained at a wavelength of maximum peak intensity of $I_{int}(\theta,\lambda)$ in Eq. (1) with the conditions of $\Delta_{FP} = 2\pi m_{FP}$ and $\Delta_{TBI} = 2\pi m_{TBI}$, where m_{FP} and m_{TBI} are the lowest integers. It is found that the values of m_{TBI} in the most devices become zero because the thickness of EML should be thin. Also, the values of m_{FP} become zero or one depending on the thickness of ITO film and the hole transfer layer.

In our previous research, we reported the determination of an optimized Alq_3 layer thickness in OLEDs [11]. The optimum Alq_3 thickness was obtained at $\Delta_{TBI} = 0$ and $\Delta_{FP} = 2\pi$. The experimental EL spectra were in good agreement with the simulated EL spectra from Eq. (1).

Figures 2 (a) and (b) show the variation of phase change on reflection at interface B as the thickness of ITO film is changed. At 199 nm ITO thickness, the output radiance is maximum because Δ_{FP} is 2π as shown in Fig. 2 (a). On the other hand, the radiance of device with the condition of $\phi_B = \pi$ is reduced. However, if TiO_2 dielectric layer is inserted between ITO film and substrate, the phase change on reflection changes from π to 2π . TiO_2 dielectric layer plays a role to enhance the reflectance on interface B as the

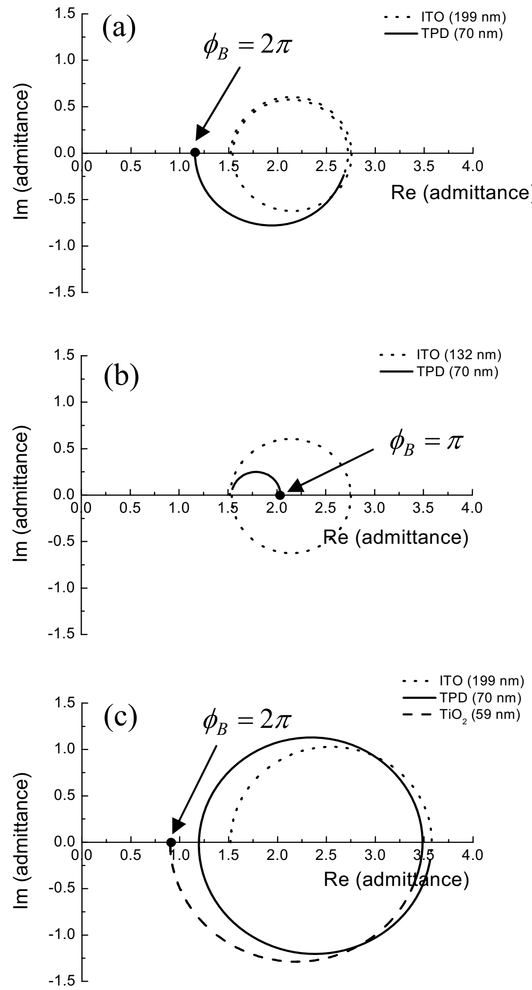

Fig. 2. Phase change on reflection calculated using admittance diagram (a) $\phi_B = 2\pi$ [TPD (70 nm)|ITO (199 nm)|glass] (b) $\phi_B = \pi$ [TPD (70 nm)|ITO (132 nm)|glass] (c) $\phi_B = 2\pi$ [TPD (70 nm)|ITO (132 nm)|TiO_2 ($\lambda/4$)|glass].

finial admittance is away from the admittance of incident medium as shown in Fig. 2 (c).

3. Optical simulation

We have designed the OLED multilayer structures at $\phi_B = 2\pi m_{FP}$ and $\phi_B = (2m_{FP}+1)\pi$ to investigate the Fabry-Perot multiple beam interference effect in Eq. (1). Figures 3 (a) and (b) show the simulated radiance at $\theta = 0$ for the various OLEDs with $\phi_B = 2\pi m_{FP}$ and $\phi_B = (2m_{FP}+1)\pi$, respectively. The radiance of OLEDs at $\phi_B = 2\pi$ (Type A-I; [Al|Alq_3|TPD|ITO (199 nm)|glass]) is higher than that at $\phi_B = \pi$ (Type A-II; [Al|Alq_3|TPD|ITO (132 nm)|glass]) as shown in Fig. 3(a). However, the reflectance phase of Type A-II is changed by the dielectric multilayers. As a result, the radiance of OLED with a single TiO_2 dielectric layer in Type B-II is higher than that of an optimized OLED without a dielectric layer (Type A-I). The radiance of OLEDs with three dielectric multilayers shows also good performance in the forward direction. On the other hand, the radiance of OLEDs with dielectric layers in Fig. 3 (b) decreases because the phase is changed from $\phi_B = 2\pi$ to $\phi_B = (2m_{FP} + 1)\pi$, where $m_{FP} = 1,2,3\cdots$.

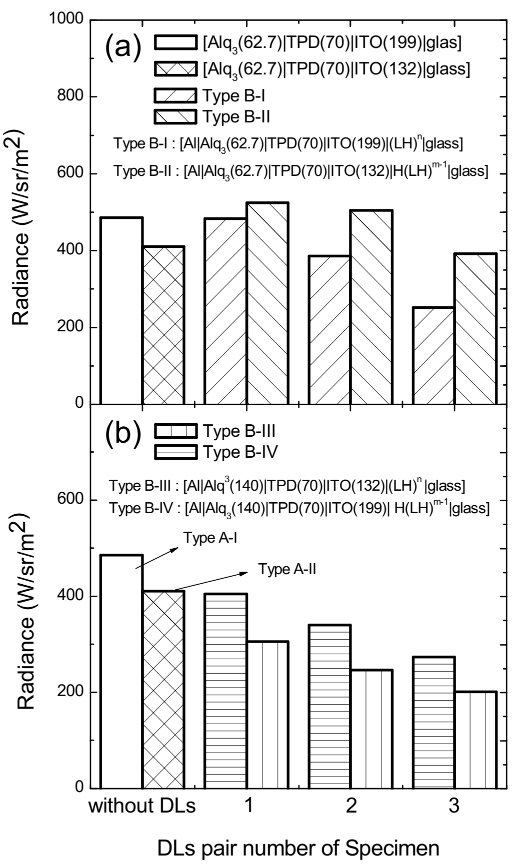

Fig. 3. Simulated radiance in forward direction for various Type B OLEDs as the pair number of dielectric layers increases. (a) Type B-I and Type B-II (b) Type B-III and Type B-IV. (H : TiO_2, L : SiO_2)

From this result, we have selected the three types, i.e., Type A-I, Type B-II with single TiO_2 layer, and Type B-II with three dielectric multilayers, and simulated the spectral radiance, angular dependence and variation of color coordinates as shown in Fig. 4. As a result, peak EL intensity is enhanced as the number of dielectric layer is increased and the FWHM is reduced due to the Fabry-Perot effect.

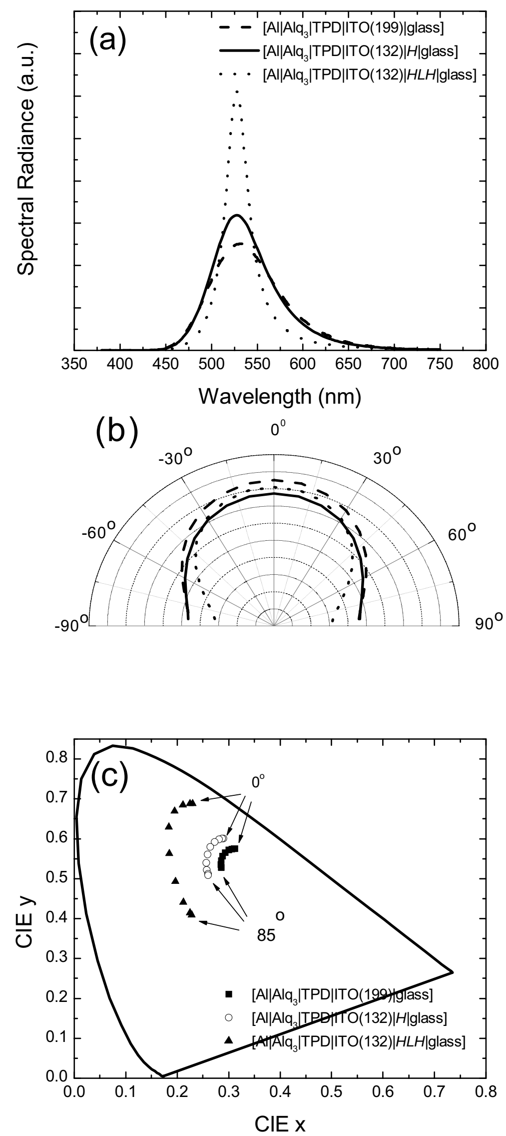

Fig. 4. (a) Simulated spectral radiance (b) angular dependence (c) variation of color coordinates for three types.

Therefore, the narrow FWHM of the OLEDs with three dielectric multilayers leads to higher color purity. However, the radiance of these devices is quickly decreased as viewing angle is increased. Obviously, the relationship between large viewing angle and color purity should be traded off. The results show that the best structure of the OLEDs in the limited viewing angle is a device with three dielectric multilayers. Furthermore, we found out that the OLEDs with a single TiO_2 layer are also good candidate of OLEDs used in wide viewing angle.

4. Conclusion

We designed the high efficient OLEDs through the control of reflectance phase on interface B using the optical model which is based on optical thin-film theory. We found that a TiO_2 dielectric layer plays a role in changing the reflectance phase on interface B and enhancing the radiance of OLEDs. The OLEDs with a single TiO_2 dielectric layer show the enhanced radiance in all direction compared with the optimized OLEDs at $\phi_B = 2\pi$ and $\phi_B = \pi$ on interface B. It suggests that the proposed optical model is a useful tool to optimize and design the high efficient OLEDs.

5. Acknowledgements

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6. References

[1] Y. Fukuda, T. Watanabe, T. Wakimoto, S. Myaguchi, and M. Tsuchida, Synt. Met. **111-112**, 1 (2000).

[2] Y. R. Do, Y.-C. Kim, Y.-W. Song, and Y.-H. Lee, J. Appl. Phys. **96**, 7629 (2004).

[3] T. Tsutsui, M. Yahiro, H. Uokogawa, K. Kawanom, and M. Yokoyama, Adv. Mat. **13**, 1149 (2001).

[4] S. Möller, and S. R. Forrest, J. Appl. Phys. **91**, 3324 (2002).

[5] T. Yamasaki, K. Sumioka, and T. Tsutsui, Appl. Phys. Lett. **76**, 1243 (2000).

[6] V. Cimrová, and D. Neher, J. Appl. Phys. **79**, 3299 (1996).

[7] B.-Y. Jung, and C. K. Hwangbo, 3rd ISAPST Conference (2005), J. Korean Phys. Soc. accepted.

[8] S. K. So, W. K. Choi, L. M. Leung, and K. Neyts, Appl. Phys. Lett. **74**, 1939 (1999).

[9] H. Kuma, H. Tokairin, K. Fukuda, and C. Hosokawa, Proc. SID, 1276 (2005).

[10] T. Shiga, H. Fujikawa, and Y. Taga, Proc. SID, 547 (2005).

[11] B.-Y. Jung, and C. K. Hwangbo, J. Korean Phys. Soc.**48**, 1281 (2006).