Thin-film encapsulation for top-emitting organic light-emitting diode with inverted structure

Chaoping Chen (陈超平)[1], Hongjing Li (李洪婧)[1], Yong Zhang[2], Changbum Moon[2], Woo Young Kim[2], and Chul Gyu Jhun[2*]

[1]*National Engineering Lab for TFT-LCD Materials and Technologies, Department of Electronic Engineering, Shanghai Jiao Tong University, Shanghai 200240, China*

[2]*School of Green Energy and Semiconductor Engineering, Hoseo University, Asan, Chungnam, 336-795, Korea*

[*]*Corresponding author: cgjhun@hoseo.edu*

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We theoretically study the light outcoupling efficiency of top-emitting organic light-emitting diode (OLED) with inverted structure and thin-film encapsulation. Thin-film optics is used to optimize the layer thickness to obtain high transmittance. Dipole mode is used to analyze the light outcoupling efficiency of the top-emitting OLED. Through this process, we can optimize the thin-film thickness with high transmittance and optimize the outcoupling efficiency of OLED. Compared with previous research, the current design method is a novel process.

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Organic light-emitting diode (OLED) is considered the next-generation display technology owing to its superior performance, such as fast response, wide viewing angle, and high contrast ratio[1-4]. The response time of OLED is a few tens of microseconds. The viewing angle is over 170°, and the contrast ratio is over 70,000 for all viewing angles. However, two major issues limit this technology from immediately taking over the dominant liquid crystal display[5−7]. One issue is the manufacturing cost of OLEDs. To reduce cost, the inverted OLED structure is preferred because the driving backplane can be based on n-channel amorphous-Si thin-film transistor[8]. The other issue is the lifetime of OLEDs. To have a minimum lifetime of over 10000 hours, the encapsulation layer of OLEDs should have a water vapor transmission rate of less than 10^{-6}g/(m^2 day)[9]. Although thin-film encapsulation formed by multiple alternating organic and inorganic layers can significantly improve the lifetime, light outcoupling efficiency η_{out} should also be considered, especially for top-emitting OLEDs[8]. As a crude approximation, η_{out} can be estimated as $1/(2n^2)$ for isotropic emitters, where n is the refractive index of the emitting organic layer[10]. To improve the external quantum efficiencies, many methods have been proposed, e.g., scattering[11] and grating[12]. However, these methods are unsuitable for displays where fine picture resolution is needed. In this letter, we adopt thin-film encapsulation for a top-emitting, inverted OLED, whose structure and light outcoupling efficiency are to be studied at length.

We calculate thin-film optics to design the multi-layer thin-film encapsulation for high optical transmittance[13−15]. The transfer matrix of multi-layer structure is written as[16]

$$\begin{bmatrix} B \\ C \end{bmatrix} = \left\{ \prod_{j=1}^{K} \begin{bmatrix} \cos\delta_j & \dfrac{i}{\eta_j}\sin\delta_j \\ \eta_j \sin\delta_j & \cos\delta_j \end{bmatrix} \right\} \begin{bmatrix} 1 \\ \eta_0 \end{bmatrix}, \quad (1)$$

where η_j is the admittance of the j layer, and δ_j is the phase difference when light propagates in the j layer. In the case of oblique incidence with angle θ_j, the admittance is divided into two polarization components, i.e., P and S, whose admittances are respectively given as

$$\eta_{Pj} = \frac{\eta_j}{\cos\theta_j}, \quad \text{and} \quad \eta_{Sj} = \cos\theta_j \eta_j. \quad (2)$$

The average transmittance can then be calculated by $T_{\text{avg}} = (T_s + T_p)/2$.

In absorbing media, we ensure that the phase factors are consistent. Thus, the phase differences in j layer can be expressed by

$$\delta_j = \frac{2\pi}{\lambda}(n_j - ik_j)\cos\theta_j = \delta_{1j} - \delta_{2j}, \quad (3)$$

where δ_{1j} and δ_{2j} are real numbers. We can apply the transfer matrixes in multi-layers to calculate both reflection and transmission of the device. The reflection and transmission can respectively be written as

$$R = \left(\frac{\eta_0 B - C}{\eta_0 B + C}\right)\left(\frac{\eta_0 B - C}{\eta_0 B + C}\right)^*, \quad (4)$$

$$T = \frac{4\eta_0\eta_{K+1}}{(\eta_0 B + C)(\eta_0 B + C)^*}. \quad (5)$$

By using the above equations, we can numerically analyze the transmission spectrum $T(\lambda)$ and the reflection spectrum $R(\lambda)$. By simulating the optical characteristics of our OLED device, we can optimize the multi-layer encapsulation structure from one pair to five pairs. The one-pair structure is schematically depicted in Fig. 1. The refractive indices of each material used are listed in Table 1.

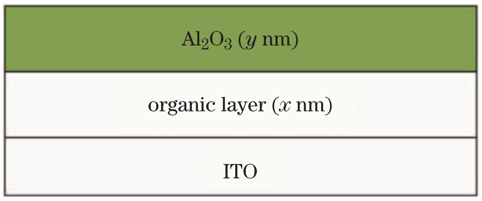

Fig. 1. One-pair encapsulation structure.

Table 1. Refractive Indices Used in Our Simulation

	ITO	Organic layer	Al_2O_3
n	1.92	1.52	1.66

We firsly calculate the transmittance with respect to different thicknesses of organic and inorganic layers, as shown in Fig. 2(a). According to the contour map, to achieve maximum transmittance of the encapsulation layer, the optimum thicknesses of organic and inorganic layers should be 30 and 60 nm, respectively. We will then increase the number of organic/inorganic layer pairs from one pair to five pairs. Figure 2(b) plots the calculated transmittance versus the pair numbers.

The analysis of light outcoupling efficiency must consider near-field phenomena and the photonic mode density caused by the presence of thin organic films. The traditional approach for such device simulation is known as the dipole model[17]. Our simulations on the outcoupling efficiency are also based on this model, in which the dipole source takes the form of a forced, damped harmonic oscillation[17]:

$$\frac{\mathrm{d}^2p}{\mathrm{d}t^2}+\omega_0^2p=\frac{e^2}{m}E_\mathrm{r}-b_0\frac{\mathrm{d}p}{\mathrm{d}t}, \tag{6}$$

where m is the effective mass of the dipole, ω_0 is the oscillation frequency in the absence of all damping, E_r is the reflected field at the dipole position, and b_0 is the damping constant in the absence of mirror.

Using this model, all dipole orientations may be considered as a combination of perpendicular and parallel dipole components as[18]

$$\frac{b}{b_0}=(1-q)+q\int_0^\infty F(u)\mathrm{d}u, \tag{7}$$

where u represents the in-plane component of the wave vector, q is the internal quantum efficiency of the emitting dipoles, and $F(u)$ is the power dissipation density per unit du. According to these theories, we can simulate the power dissipation and light outcoupling efficiency for OLEDs with air, waveguide, and surface plasmon polariton (SPP) modes. The term that denotes the power dissipation density per unit du can be calculated for randomly oriented dipoles as

$$F=1/3F_{\mathrm{TM}v}+2/3(F_{\mathrm{TM}h}+F_{\mathrm{TE}h}), \tag{8}$$

where the power densities are given by[19]

$$F_{\mathrm{TM}v}=\frac{3}{2}\mathrm{Re}\left[\frac{u^3}{\sqrt{1-u^2}}\frac{(1+a_\mathrm{TM}^+)(1+a_\mathrm{TM}^-)}{(1-a_\mathrm{TM})}\right], \tag{9}$$

$$F_{\mathrm{TM}h}=\frac{3}{4}\mathrm{Re}\left[\frac{u}{\sqrt{1-u^2}}\frac{(1-a_\mathrm{TM}^+)(1-a_\mathrm{TM}^-)}{(1-a_\mathrm{TM})}\right], \tag{10}$$

$$F_{\mathrm{TE}h}=\frac{3}{4}\mathrm{Re}\left[u\sqrt{1-u^2}\frac{(1+a_\mathrm{TE}^+)(1+a_\mathrm{TE}^-)}{(1-a_\mathrm{TE})}\right], \tag{11}$$

where Re[ ] stands for the real part of the complex quan-tity, $a_{\mathrm{TM,TE}}^+=r_{\mathrm{TM,TE}}^+\exp(2jk_{z,e}z^+)$, $a_{\mathrm{TM,TE}}^-=r_{\mathrm{TM,TE}}^-\exp(2jk_{z,e}z^-)$, and $a_{\mathrm{TM,TE}}=a_{\mathrm{TM,TE}}^+a_{\mathrm{TM,TE}}^-r_{\mathrm{TM,TE}}^+$. Here, $r_{\mathrm{TM,TE}}^+(r_{\mathrm{TM,TE}}^-)$ denotes the reflection coefficient for the waves travelling from the emissive layer in the upward (downward) direction for TM and TE polarized waves, and $z^+(z^-)$ is the distance of the emitting dipoles from the top (bottom) interface of the active layer. $k_{z,e}=k_e\sqrt{1-u^2}$ denotes the out-of-plane component of the wave vector for the propagation within the emitting layer, and the reflection coefficients are calculated by the multi-layer thin-film transfer matrix approach.

Figure 3 shows the structure of a top-emitting OLED with multi-layer encapsulation for simulation. The dipole energy outcoupling and absorption depend on the dipole direction. Figure 4 shows the calculated power dissipation of this structure depending on the dipole directions,

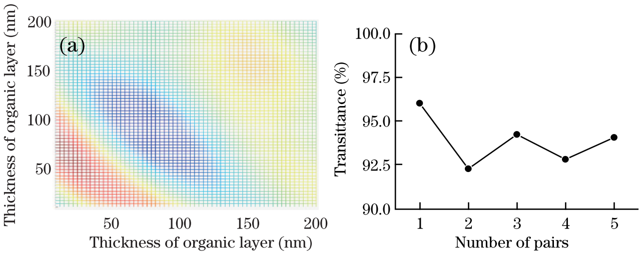

Fig. 2. (a) Transmittance contour of one-pair encapsulation structure with respect to different thicknesses of organic and inorganic layers and (b) variation of transmittance versus the number of pairs of encapsulation.

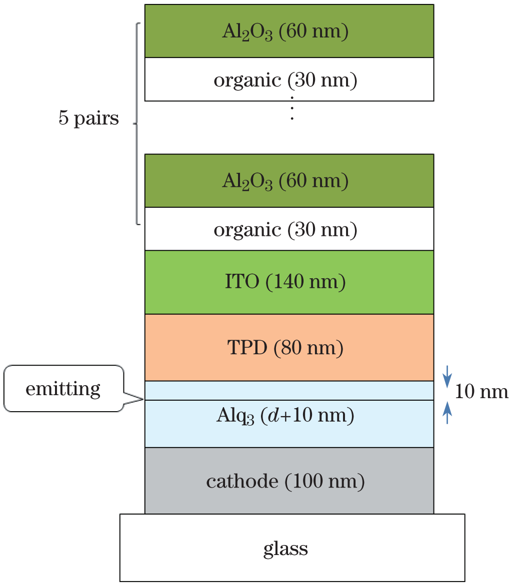

Fig. 3. Simulated structure of a top-emitting OLED with multi-layer encapsulation.

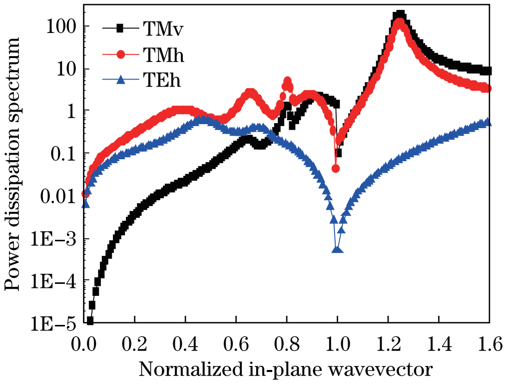

Fig. 4. Power dissipation of the multi-layer thin-film OLED depending on the dipole directions.

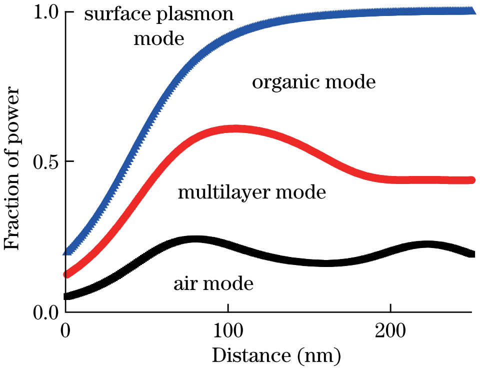

Fig. 5. Fraction of power dissipation with different modes as d changes from 1 to 250 nm.

where the dipole, which emits light with a wavelength of 500 nm, is located at d=75 nm. The optical loss is a function of the value u. When $u < 1/1.758 = 0.569$, the region has propagating components in air as air mode, which is the outcoupling energy component. When $0.569 < u < 1.46/1.758 = 0.83$, the region has propagating components in multi-layer encapsulation as multi-layer mode. When $0.83 < u < 1$, the region has propagating components in organic layers as organic mode. When $u > 1$, the region has propagating components in evanescent waves, and a peak is observed near $u = 1.25$ for TM polarization. This peak can be attributed to SPPs at the emitting layer or at the cathode interface.

The fraction of power dissipation can be calculated with respect to different contributions. Figure 5 shows the fraction of power dissipation with different modes as d changes from 1 to 250 nm. The power is effectively radiated by the dipoles to the far field, which is the air mode determining the useful OLED light emission efficiency. To achieve higher outcoupling efficiency, we choose the distance d = 75 nm for the top-emitting OLED with a maximum efficiency of 25%.

In conclusion, on the basis of the theory of thin-film optics, we simulate the outcoupling efficiency of a top-emitting OLED with multi-layer thin-film encapsulation and optimize the layer thicknesses to obtain high transmittance. The thin-film encapsulation consists of multiple alternating organic and inorganic layers. According to the numerical calculation, the optical transmittance with one pair and five pairs of organic/inorganic layers are 96% and 94%, respectively. By using the dipole model and by considering the surface plasmon resonance effects, we calculate the power dissipation of the top-emitting OLEDs. The simulation results indicate that the light outcoupling efficiency of the top-emitting OLED with optimized multi-layer encapsulation is 25% when the emitting dipole is located at 75 nm away from the cathode.

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