High-contrast and high-efficiency top-emitting organic light-emitting devices

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ABSTRACT The reflection properties of top-emitting organic light-emitting devices with different electrodes and organic layers were calculated. The results guided the fabrication of a high-contrast device: Au/copper phthalocyanine (CuPc: 35 nm)/N,N′-bis-(1-naphthyl)-N,N′diphenyl-1,1′biphenyl-4,4′diamine (NPB: 15 nm)/tris(8-hydroxyquinoline) aluminum (Alq3: 50 nm)/Sm (35 nm)/Alq3 (65 nm). The device has a contrast ratio of 8.3 : 1 at a luminance of 300 cd/m² under 1000 lx ambient light, and a maximum luminance and efficiency of 5000 cd/m² and 4.14 cd/A, respectively. The high contrast is attributed to the moderate reflection of Au at 380–550 nm, low reflection of Sm in the visible range, and high absorption of CuPc at 600–700 nm.

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1 Introduction

Top-emitting organic light-emitting devices (TEOLEDs) are required for active-matrix organic light-emitting devices (AMOLEDs) fabricated on crystalline silicon substrate. They are also suitable for making microdisplays due to the high-level integration necessary for the driver circuits with the matrix structure of OLEDs on a silicon chip. High-efficiency and high-luminance TEOLEDs based on different device structures or materials have been reported [1–5]. For many applications, high-contrast OLEDs that are easily viewable in illumination condition are important. To this end, extensive efforts have focused on improving the contrast ratio of traditional bottom-emitting OLEDs in recent years [6–11]. Yet, there are few reports on the contrast ratio of TEOLEDs [12].

In this paper, we calculate and analyze the reflection properties and contrast ratios of TEOLEDs with different electrodes (Au, Ag and Sm) and organic layers. The theoretical results are then used to guide the design and fabrication of a high-efficiency and high-contrast TEOLED. Factors contributing to the high contrast and microcavity effect of the device are discussed.

2 Experimental details

The device with a structure of glass substrate/Au (100 nm)/copper phthalocyanine (CuPc: 35 nm)/N,N′-bis-(1-naphthyl)-N,N′diphenyl-1,1′biphenyl-4,4′diamine (NPB: 15 nm)/tris (8-hydroxyquinoline) aluminum (Alq3: 50 nm)/Sm (35 nm)/Alq3 (65 nm) (device F) was fabricated by thermal evaporation. In the device, the Au, CuPc, NPB and Sm were used as the anode, hole-injection layer (HIL), hole-transporting layer (HTL) and cathode, respectively. A 50-nm-thick and 65-nm-thick Alq3 layer was used as the electron-transporting/emitting layer and the dielectric index-matching layer, respectively. All the films were deposited at pressures below $2 \times 10^{-6}$ Torr. Deposition rates were measured with a quartz oscillating thickness monitor and the deposition rates of organic materials and metals were controlled to be about 2 Å/s. The characteristics of the current–voltage-luminance and EL spectra were measured in air at room temperature with a programmable Keithley model 237 power supply and a photo-research PR650 spectrometer. Optical constants of the organic materials and the reflection spectrum of the device were measured with variable angle spectroscopic ellipsometry (VASE).

3 Results and discussion

Reflection spectra of TEOLEDs with different electrodes and organic layers were calculated by using a transfer matrix method. First, the reflection spectra of the devices using 50 nm NPB as HTL and 50 nm Alq3 as emitting layer with different electrodes were analyzed. Device A with Ag as anode and semitransparent Ag as cathode has the highest reflection among all the devices (Fig. 1a). Using Au as an anode (device B), we found that reflection decreases remarkably at 380–550 nm because Au has lower reflection than Ag at 380–550 nm. When Sm is used as a cathode (device C), the reflection decreases remarkably at 600–780 nm because of the lower reflection of Sm than that of Ag in the visible range. We can see that the device with Au as an anode and Sm as
The cathode (device D) has an average reflection of about 25%. To further decrease optical reflection, CuPc was used as the HIL to make use of its high absorption at 600–700 nm. In comparisons between devices C and D, the reflection of devices E and F decreased further, with device F having an average reflection as low as 15% in the visible region.

Luminous reflectance, $R_L$, of a device is defined as:

$$R_L = \frac{\int_{\lambda_1}^{\lambda_2} V(\lambda) S(\lambda) R(\lambda) \, d\lambda}{\int_{\lambda_1}^{\lambda_2} V(\lambda) S(\lambda) \, d\lambda};$$

where $\lambda_1$ and $\lambda_2$ are 380 nm and 780 nm respectively, $V(\lambda)$ is the standard photonic curve, $R(\lambda)$ the optical reflection of the device, and the $S(\lambda)$ the spectral power distribution of the light source D65. The calculated luminous reflection of device F is only 13%, which is about one fourth of that of device A. Figure 1b shows the calculated and measured reflection spectra of device F at $45^\circ$. The reflection of the device at $45^\circ$ is lower than that at $0^\circ$, and the experimental data agree reasonably well with the calculated values. We calculated the reflection at different angles of incidence (only data at $0^\circ$ and $45^\circ$ are shown here) and found the reflection at $0^\circ$ is the highest. Therefore, for real cases, the luminous reflection of the device at viewing angles larger than zero degree is lower than the calculated value.

Figure 2 shows the calculated contrast ratios of the OLEDs under different ambient illumination. The pixel contrast ratio (PCR) was calculated as $PCR = (L_{\text{on}} + L_{R}\lambda)/(L_{\text{off}} + L_{R}\lambda)$, where $L_{\text{on}}$ and $L_{\text{off}}$ are the brightness of a pixel at on- and off-state, respectively, $L$ is the ambient illumination, and $R_{L}$ is the luminous reflectance. In the calculation, the brightness of the device at on- and off-state is set, respectively, to be 300 and 0 cd/m$^2$. The contrast ratio of device F is calculated to be 8.3 : 1 under an ambient illumination of 1000 lx, which is about three times higher than that of devices A and G (conventional bottom-emitting device with the structure of ITO/NPB (50 nm)/Alq$_3$ (50 nm)/Mg:Ag). Besides, the improvement of the contrast is about 50% under 10000 lx strong ambient lighting. The low-reflection TEOLED (device F) shows sufficient contrast ratio which is suitable for outdoor applications.

Figure 3 shows (a), the characteristics of current density–voltage and current density–brightness, and (b), the current density–current efficiency of device F and G. The turn-on voltage of the device F is less than 6 V while the maximum luminance and current efficiency are 5000 cd/m$^2$ and 4.14 cd/A, respectively. We also can see that the current density of device F is much lower than that of device G while the luminance of device F is higher than that of device G at the same current density. As a result, the current efficiency of device F is higher than that of device G. It is considered that the presence of CuPc can improve hole-injection efficiency from the Au anode. In addition, the high optical transmission (43%) of the Sm/Alq$_3$ film, the excellent electron-injection property of the Sm cathode, and the microcavity resonant effect of the TEOLED also contribute to the high device efficiency. Although the drive voltage of device F is higher than that of device G, it can be decrease by using LiF or CF$_3$ modified Au anode [13] while the contrast of the device will not be worsen. We found that the drive voltage of TEOLED with Au, Au/LiF and device G for a luminance of 100 cd/m$^2$, a typical luminance for AMOLEDs, are 9.3 V, 7.0 V and 6.4 V, respectively. It suggested that the luminance and efficiency of the TEOLED could be further improved by using optimum treatment Au anode and new emitting materials.