

Contrast-enhancement in organic light-emitting diodes

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Abstract: A high-contrast organic light-emitting diode (OLED) structure is presented. Because of poor contrast of conventional OLED resulting from high reflective metal cathode, the hybrid cathode structure was developed for low reflectivity. It consists the semitransparent cathode layers, passivation layers and a thick light-absorbing film. By optical reflectivity measurement and OLED electrical characterization tests for both OLED with the hybrid cathode and conventional OLED, it was found that the spectrum reflectance of OLED with hybrid cathode is among 8%-12%, about eight times lower than the conventional one when the two types of devices have similar turn-on voltages and current-voltage characteristics. The hybrid cathode for the high-contrast OLED is easily fabricated and its optical reflectance is slightly dependent on wavelength.

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1. Introduction

Since the demonstration of organic light-emitting diodes (OLEDs) operating at reasonable low voltage, organic electronics have been attracting a great interest due to lower cost and new potential niches, like large-area flat displays [1,2]. The conventional OLEDs have a transparent substrate, typically indium tin oxide (ITO) glass, through which the light is emitted, and a surface metallic cathode such as Mg:Ag, which is highly reflective. In high ambient luminescence, the metallic cathode reflects incident ambient light and leads to the decrease of contrast ratio of display based on OLEDs.

Many approaches have been worked out to increase the contrast ratio of OLEDs [3-10]. The most common approach is the use of circular polarizers, which can be bonded to the outside surface of the OLEDs and enhance the contrast ratio of display [3]. Because the circular polarizer is not an integral part of the OLEDs, this approach adds extra cost to devices. Recently, several other approaches have been developed to reduce the reflectivity of cathode and increase contrast ratio of OLED [4-10]. These approaches are all based on the principle of destructive-optical-interference. For example, in Krasnov et al. [4,5], Hung et al [6,7], Feng et al. [8], and recent literatures [9,10], cathodes of OLEDs based on destructive-optical-interference filter were proposed to efficiently decrease reflection of ambient luminescence by the cathode itself. The structure of these cathodes comprises a thin semi-transparent metal layer, a phase-changing layer and a thick reflective metal layer. The reflection of these cathodes was reduced by the destructive-optical-interference by the two light waves, one reflected from the front thin semi-transparent metal layer and the other having a π phase difference reflected from the thick reflective metal layer. According to this principle, a contrast-enhancing stack (trademarked Black LayerTM) was also developed to reduce the reflectivity of the cathode by Luxell Technologies Co., Ltd [4]. However, these approaches are quite complex and require stringent film deposition. In this paper, a simple hybrid cathode structure of OLED with thick light-absorbing film instead of destructive-optical-interference filter is presented to reduce reflection of ambient luminescence. This hybrid cathode consists of the semitransparent metallic layers, transparent passivation layers and a thick light-absorbing layer. Compared with the cathode with destructive-optical-interference filter, the hybrid cathode is easily fabricated and controllable. And the OLEDs with hybrid cathode have higher contrast ratio of display than those of the conventional metallic cathode but have similar turn-on voltages and current-voltage characteristics with those of conventional ones.

2. Experimental results and discussion

Figure 1 shows the structure of the OLEDs with the hybrid cathode (Device 2) and the conventional metallic cathode (Device 1). The following process was used to fabricate the OLED. Indium-tin oxide (ITO)-coated glass substrates with a surface resistance of $10\sim 20\ \Omega/\text{sq}$ were cleaned in ultrasonic baths of acetone and methanol. N, N'-diphenyl - N, N'-bis (1,1'-biphenyl)-4,4'-diamine (NPB) and Alq were used as the hole transporting layer and emitting layer, respectively. The layers of NPB, and Alq were all deposited by vacuum deposition (below $10^{-3}\ \text{Pa}$). As for device 1 in Fig. 1, the metallic cathode of the conventional OLED consists of two layers, one is the mixture layer of magnesium and silver with the ratio of 10:1, 150nm. And the other is a 50nm-thick Ag layer. For the device 2 in Fig. 1, the hybrid cathode comprises three parts: one is the semi-transparent metallic layers, which consists of a layer of Mg:Ag(10:1) and Ag layer. The thin layer of Mg:Ag serves as electron injection layer and the Ag layer is responsible for the electron conduction. In our experiment, if Mg:Ag is less than 8 nm, the decrease of device performance was observed. Hence, in order to keep good optical transmission of Mg:Ag layer, we deposited the Mg:Ag layer with 8nm. Because Ag layer was required for both the good electron conduction and enough optical transmission, 15nm-thick Ag layer was also optimal in our experiment. This structure of semi-transparent metallic layers is different with the combination of the thin Mg:Ag and ITO

layers used in transparent OLEDs by Dr. Forrest's group[11]. The second is the transparent passivation layers, a combination of a 50nm-thick Alq layer and 15nm-thick titanium nitride layer. And the third is the 600 μm -thick light-absorbing layer, which is a mixture of polyacrylate and black dye. Current-voltage and luminance-voltage characteristics of OLEDs were carried out in ambient atmosphere using a Keithley 4200 semiconductor characterization system. A UV/VIS spectrophotometer (Shimadzu, UV-2100s) was used to measure the spectrum reflectance of Device 1 and 2.

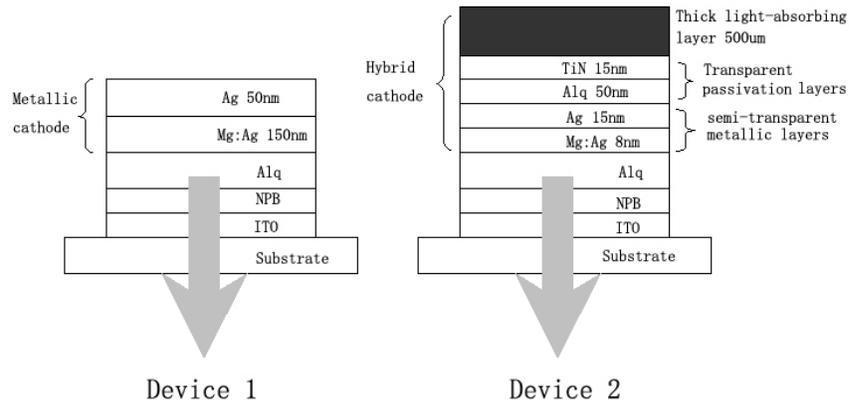


Fig. 1. Schematic diagram of the OLED with conventional metallic cathode (Device 1) and hybrid cathode (Device 2)

Figure 2 shows the current-voltage (I-V) and luminance-voltage (L-V) characteristics of Device 1 and 2. As shown in Fig. 2(a), no notable difference in I-V behavior can be found between Device 1 and 2. The luminescence characteristic of Device 1 is better than that of Device 2, shown in Fig. 2(b). The reduced luminescence of Device 2 results from the absorption of light from the emitting-layer by the hybrid cathode of device.

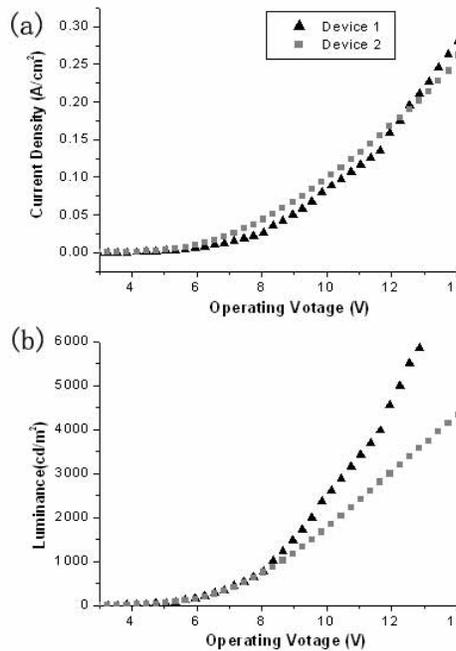


Fig. 2. I-V and L-V characteristics of Device 1 and Device 2

The spectrum reflectance of Device 1 and 2 are measured from wavelength 400nm to 800nm, shown in Fig. 3. It is clear that the spectrum reflectance of Device 2 is lower than that of Device 1. Unlike the contrast-enhancement based on the destructive-optical-interference [4-10], the spectrum reflectance by the hybrid cathode in this paper is of little dependence on wavelength. It is known that the luminescence reflectance of an OLED can be expressed as [7]

$$R_L = \frac{\int_{\lambda_1}^{\lambda_2} V(\lambda)S(\lambda)R(\lambda)d\lambda}{\int_{\lambda_1}^{\lambda_2} V(\lambda)S(\lambda)d\lambda} \quad (1)$$

where $V(\lambda)$ is the standard photonic curve, $S(\lambda)$ is the spectrum of Alq in our experiment and $R(\lambda)$ is the spectrum reflectance in Fig. 2. We chose λ_1 and λ_2 as 400nm and 700nm. According to Eq. (1), the luminescence reflectance of Device 1 and 2 are 82.5% and 13.7%, which include the luminescence reflectance of glass substrate (about 4%). If we excluding the effect of glass substrate on the luminescence reflectance, the luminescence reflectance of Device 2 is 9.7%, which is about 8 times lower than that of Device 1, which is 78.5%.

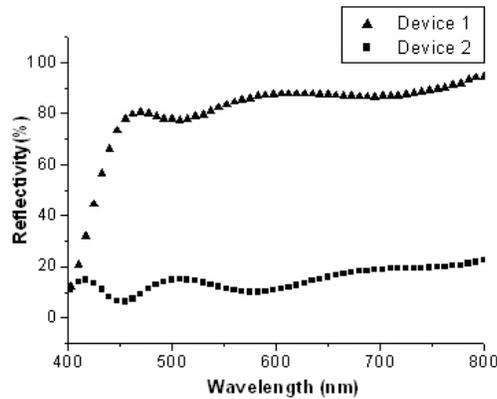


Fig. 3. The measured spectrum reflectance of Device 1 and Device 2

The lower luminescence reflectance of OLED can lead to higher contrast-ratio (CR) of display. The contrast-ratio of display is:

$$CR = \frac{L_{\max} + L_{\text{ambient}}}{L_{\min} + L_{\text{ambient}}} \quad (2)$$

Where L_{\max} is the maximum pixel luminance, L_{\min} is the minimum pixel luminance, and $L_{\text{ambient}} = R_L E_{\text{ambient}} / \pi \cdot E_{\text{ambient}}$ is the ambient illumination, and R_L is the luminescence reflectance. By Eq. (2), CR is calculated under 140 lx of ambient lighting, shown in Fig. 4. It is found that CR of Device 2 is greatly improved and higher than that of Device 1 under the same operational voltage. Figures 5(a), (b) and (c) present the photographs of Device 1 and 2 at 4, 5, and 6 voltage respectively under 140 lx of ambient lighting. According to Eq. (2), CR of Device 1 is about 1.3, 2.5 and 5.7 for 4, 5 and 6 operational voltage respectively. As for the Device 2, CR was increased to about 2.9, 10.4 and 31 for the 4, 5 and 6 operational voltage respectively. In Fig. 5, it is quite apparent that the Device 2 is more legible than Device 1. Generally speaking, the structure of hybrid cathode of Device 2 can be optimized further for bigger CR. For instance, the semi-transparent metallic layer can be replaced with ultrathin layer of LiF/Al/Ag [12], layers of MgAg(10nm)/ITO(40nm) [11] or rare earth metal layer [13,14]. More investigations are in progress.

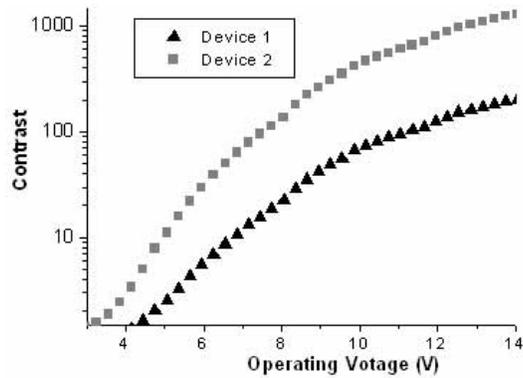


Fig. 4. Contrast-ratio of Device 1 and Device 2

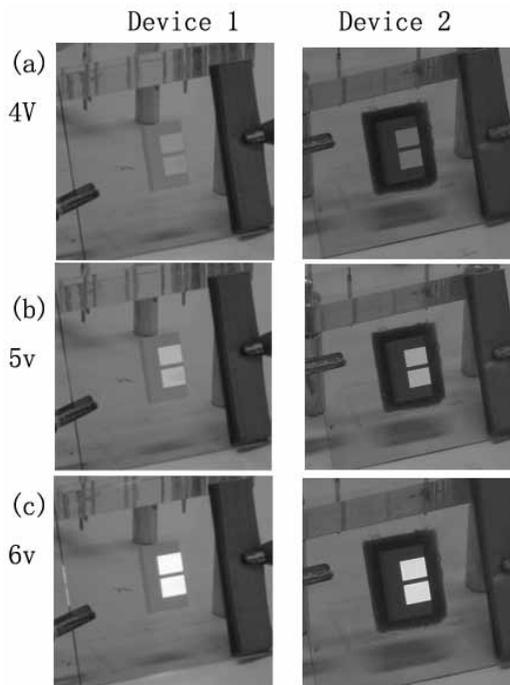


Fig. 5. Photographs of Device 1 and Device2 at 3, 4 and 5 operational voltages.

3. Conclusion

In conclusion, we demonstrated a high-contrast OELD with lower reflectance cathode. The hybrid cathode comprises of the semi-transparent metallic layers, passivation layers and a thick light-absorbing layer. The luminescence reflectance of OLEDs with hybrid cathode is about 9.7%, 8 times lower than that of OLEDs with conventional metallic cathode such as Mg:Ag. And the turn-on voltage and current-voltage characteristics are not obviously influenced by the newly designed cathode. In addition, the hybrid cathode for the high contrast OLED is easy to fabricate and its spectrum reflectance is only slightly dependent on wavelength of light.

Acknowledgments

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