Improved viewing characteristics of red emission top-emitting organic light-emitting devices by integrating grating

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Abstract. An effective way to resolve the viewing-angle characteristics of microcavity red emission top-emitting organic light-emitting diodes (TOLEDs) by introducing grating and filling process into TOLEDs is demonstrated. From this approach, gradually changed cavity length can be obtained and the range of the resonant wavelength in these devices can be broadened. As a result, TOLEDs with grating exhibit a quasi-Lambertian emission pattern and have no color shift at different viewing angles. In addition, we can almost observe the same luminance and efficiency in TOLEDs with and without grating. *© 2013 Society of Photo-Optical Instrumentation Engineers (SPIE)* [DOI: 10.1117/1.OE.52.8.080502]

Subject terms: top-emitting organic light-emitting devices; microcavity effects; viewing-angle characteristics; grating.

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1 Introduction

Organic light-emitting diodes (OLEDs) have gotten more attention and great progress has been achieved in recent years. OLEDs have many merits such as self-illumination, short response time, wide operation temperature, lightweight, high luminance, flexibility, and so on, which make them suitable for next-generation flat-panel displays.[1–5] For the application of the high-quality flat-panel display, viewing-angle characteristic is a key issue. Generally, bottom-emitting OLEDs exhibit a large viewing angle and a quasi-Lambertian emission pattern, but they are not suitable for flat-panel displays since their aperture ratio is confined because of the shielding of metal wire and thin-film transistors on a substrate. Top-emitting OLEDs (TOLEDs), in which light-emitting is from the top surface of the devices, have larger aperture ratio. Taking into account the benefit of TOLEDs in the aspect of high emission efficiency, they are more suitable for the application of flat-panel displays.[4,6–10] Unfortunately, a conventional TOLED consists of a high-reflectivity bottom anode, a top semi-transparent cathode, and organic layers sandwiched in between. Inevitable microcavity effects always lead to viewing-angle dependence of the peak emission wavelength and intensity.[2,3,11,12] The resulting large variation of color and brightness at different viewing angles is a fatal disadvantage to the viewing characteristics of the OLED display. So how to suppress the viewing-angle dependence owing to microcavity effects of TOLEDs is very important for applications of TOLEDs.

2 Theory

As we know, the microcavity in conventional TOLEDs can be regarded as a Fabry–Perot cavity. The effect of microcavity effects will become stronger when the reflectivity of the anode and cathode is higher. So the usual methods to suppress the viewing-angle dependence due to microcavity effects are adding a capping layer as index matching layer on the top of emitting surface to enhance transmission[6,13,14] or using a lower-reflectivity anode.[14–16] Unfortunately, most of the reported methods only show their effects in solving the angular dependence of the emission wavelength for monochromic emission to a certain extent rather than completely, and are not effective in realizing a desired Lambertian distribution of the emission intensity. In this letter, we present an effective method to resolve the viewing-angle dependence of the devices, essentially by introducing gratings into TOLEDs. As we know, the cavity length is fixed by the distance between the two parallel electrodes and defines its resonant wavelength. In conventional TOLEDs, the anode and cathode are flat metal films paralleling each other, which makes the microcavity have only one resonant wavelength, causing the light fixed resonant condition of emitting out only in a given angle. On the contrary, the devices with introduced grating and filling process can realize gradually changed cavity lengths and, consequently, gradually changed resonant wavelengths. As a result, a change in the emission peak wavelength of the device with viewing angles has been eliminated and Lambertian emitter has been obtained. Such a strategy may be more feasible in practical application for active-matrix OLED displays.

3 Results and Discussion

The fabrication process and scheme structure of our devices is shown in Fig. 1. We used Si/SiO_2 as substrate and fabricated gratings of photoresist with holographic lithography technique. The photoresist (NOA63, Norland Products Inc.,

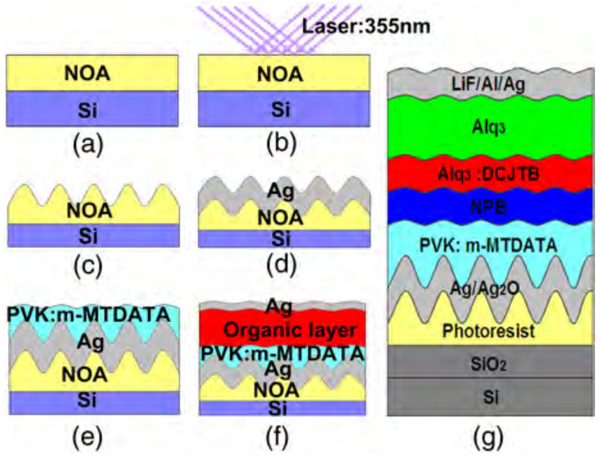

Fig. 1 Fabrication process and schematic structure of top-emitting organic light-emitting diodes with grating.

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Cranbury, NJ) diluted in acetone at a concentration of 25 mg/ml was spun-coated on the substrate at 8000 rpm speed for 30 s. The lithography experiments were performed by using a frequency-tripled Nd:YAG laser (Spectra-Physics Company, Santa Clara, CA) with 3-nm pulse width, 10-ns pulse length, 10 Hz repetition rate, and 355-nm wavelength. The period of our gratings was chosen to be 2 μm. This period value of gratings was chosen because it should be larger than wavelength scale to avoid disturbing the flat and wide-band emission by Bragg scattering in the visible region.[17–21] Then we evaporated 80 nm of Ag as anode, and the anode was exposed in UV light for 70 s to obtain a thin film of Ag$_2$O for enhancing the holes' injection. Next, a composite layer composed of poly (N-vinyl carbazole) (PVK) and 4,4′,4′′-tris (3-methylphenylphenylamino) triphenylamine (m-MTDATA) with a ratio of 1:1 by weight is spin-coated on the anode. Tetrahydrofuran was used as solvent at a concentration of 10 mg/ml. Finally, we evaporated the following layers in a thermal evaporation chamber at a base pressure of 5×10^{-4} Pa. The specific structure of our device is Ag (80 nm) / PVK: m-MTDATA / N, N′-diphenyl-N, N′-bis (1-naphthyl)-(1, 1′-biphenyl)-4,4′-diamine (8 nm)/Alq3:4-dicyanomethylene-2-t-butyl-6-(1,1, 7,7,-tetramethyljulolidyl-9-enyl)-4H-pyran (20 nm, 1 wt%)/Alq$_3$(20 nm)/LiF(1 nm)/Al(1 nm)/Ag(20 nm). The active area of the device is 2×2 mm^2. The electroluminescent (EL) spectra at different observation angles were measured by fiber optic spectrometer. The current and luminance of the devices at different voltages were measured by Keithley 2400 programmable voltage–current source and Photo Research PR-655 spectrophotometer. All of the measurements were conducted in air at room temperature.

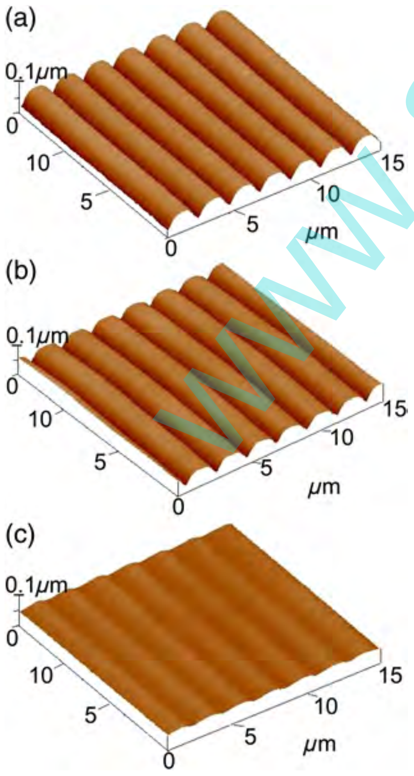

Fig. 2 Atomic force microscope figure of (a) surface morphology of photoresist; (b) Ag anode; and (c) spin-coating PVK: m-MTDATA layer.

As shown in Fig. 1, we can see that the depth of the gratings is reduced after spin-coating PVK: m-MTDATA, i.e., the lengths of the microcavity in the device are not a constant any more. It changed periodically with the fluctuation of the gratings.[22] This consideration is certified by an atomic force microscope (CSPM5000, BenYuan, China) as shown in Fig. 2. The surface morphology of photoresist, Ag anode, and spin-coating PVK: m-MTDATA layer were measured. The surface morphology was duplicated when a Ag anode was deposited on photoresist. And the grating was filled when PVK: m-MTDATA layer was spin-coated. The depths were determined to be 48.5, 46.3, and 10.1 nm. Because of the different depths of gratings on the Ag anode and cathode, the gradually and periodically changed microcavity lengths were obtained.

As shown in Fig. 3(a), the EL spectra of the devices with and without grating at different viewing angles were measured. The emission peaks of the spectra were almost same when viewing angles changed from 0 to 60 deg, while a 35 nm blueshift can be observed in the spectra of planer devices, which are shown in theb inset of Fig. 3(a). To confirm the superiority of the device with grating in color stability, we also took photos to compare the operating red devices with and without grating. The photographs of TOLEDs are shown in Fig. 3(b). The color of the planar device changed obviously. On the contrary, the color of devices with grating were almost identical, and the color shift can be observed by the naked eye. Then we measured the EL intensity of planar and grating devices at different viewing angles and

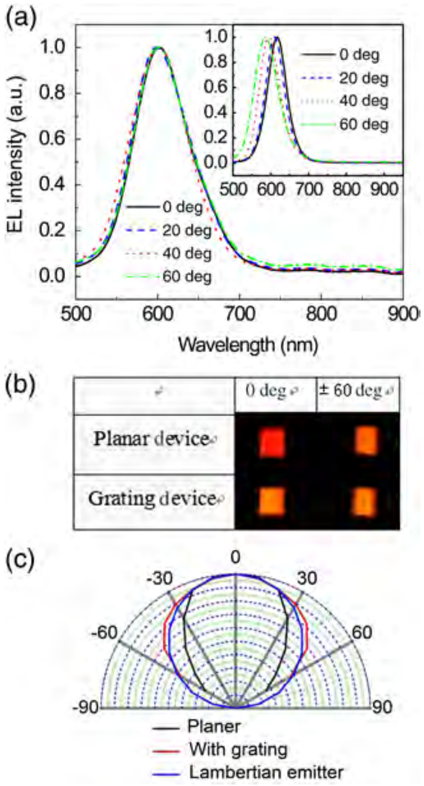

Fig. 3 (a) Normalized electroluminescence spectra of device with and without grating at different viewing angles. (b) Photograph of planar device and grating device at 5 V driving voltage at viewing angles of 0 and ±60 deg. (c) Polar plots of the emission intensities of devices with and without gratings and comparison with Lambertian emitter.

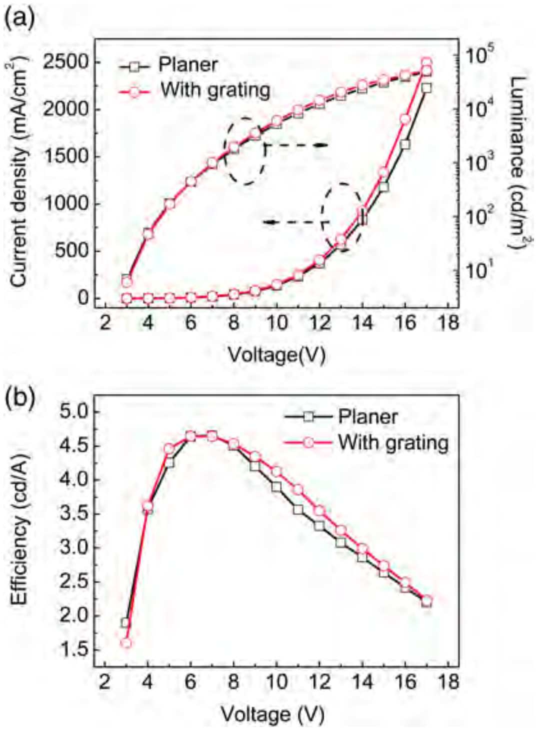

Fig. 4 (a) Current density–luminance–voltage and (b) efficiency–voltage characteristics of TOLEDs with and without grating.

compared with Lambertian emitter. As shown in Fig. 3(c), we can see that compared with planar device, the device with grating was much closer to Lambertian emitter. Especially, the EL intensity of the device with grating was a little larger than Lambertian emitter at large viewing angles such as 30 and 60 deg.

As we know, the spontaneous emission intensity can be relatively enhanced in the direction normal to the cavity axis in the noncavity devices by satisfying the resonant condition in conventional microcavity TOLEDs and results in enhanced EL efficiency in a forward direction. Figure 4 compares the current density–voltage–luminance and the efficiency–voltage characteristics of TOLEDs with and without the grating. The maximum luminance and current efficiency of TOLED with grating are 51,720 cd/m^2 at 17 V and 4.65 cd/A at 7 V, respectively, while it is 49,050 cd/m^2 at 17 V and 4.66 cd/A at 6 V, respectively, for the planar TOLEDs. Thus almost identical EL performance can be obtained in devices with and without grating. These results certified that our method can not only resolve the viewing-angle dependence in conventional TOLEDs but can also retain compared EL performances such as luminance and efficiency.

4 Conclusions

In conclusion, we solved the problem of viewing-angle dependence in TOLEDs caused by microcavity effect. The periodically and gradually changed lengths of microcavities have been achieved by introducing gratings and a filling process. Lambertian emitter has been obtained and the peak emission wavelength of the device has almost not changed with viewing angles. Moreover, introducing the gratings does not affect the efficiency of devices. The results indicate that a viewing-angle independent TOLED can be fabricated by this simple and effective method. It is essentially important for the applications in both display and solid-state lighting.

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