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Eliminate the angular dependence of blue emission top-emitting organic light-emitting devices by integrating gratings

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ABSTRACT

We demonstrate that the angular-dependence effect in blue emission top-emitting organic light-emitting diodes (TOLEDs) can be resolved in a very simple and effective way via introducing gratings and filling process. In this method, the shift of the peak emission wavelength with the viewing angle is successfully suppressed in TOLEDs. A desired emission pattern of approximately Lambertian is obtained. Moreover, we can observe almost the same current density and luminance in TOLEDs with and without gratings. Their maximal luminance are 10,776 cd/m^2 and 11,290 cd/m^2, respectively.

1. Introduction

Organic light-emitting diodes (OLEDs) are bright, emissive, colorful devices that offer quick response time, wide operation temperature, light weight, high luminance, flexibility, and so on. Display technologies using OLEDs are getting more attentions these days [1–5]. For high-quality flat panel display, viewing-angle characteristic is a key issue. Top-emitting OLEDs (TOLEDs), which are particularly suitable for high-resolution and superior information-content active matrix displays, have attracted much attention due to their higher aperture ratio than that in bottom-emitting OLEDs (BOLEDs) [4,6–10]. However, a typical TOLED consists of a high-reflective bottom anode, a semitransparent top cathode and organic layers sandwiched in between, which results in a strong microcavity effects and always leads to viewing-angle dependence of the peak emission wavelength and intensity [2,3,11,12]. For viewing characteristics of the OLEDs display, the resulted large variation of color and brightness at different viewing angles is a fatal disadvantage. Therefore, the application of TOLEDs on displays would be much promoted if these problems in the viewing characteristics can be resolved.

2. Theory

The reflective anode and semitransparent cathode are parallel with each other to form a Fabry–Pérot resonator in a conventional TOLED. As is well known to us, the cavity length is fixed by the distance between two parallel electrodes and determines its resonant wavelength. In conventional TOLEDs, the anode and cathode are flat metal films parallel to each other. Therefore, the microcavity only exhibits one resonant wavelength causing merely the light fixed resonant condition could emit out. To suppress the viewing-angle dependence due to the microcavity effect, conventional methods have been applied, such as by adding a capping layer as the index matching layer on top of the emitting surface in order to enhance transmission [6,13,14] or by using an anode with low reflectivity [14–16]. Unfortunately, most of the reported methods only show their advantages in solving the angular dependence of the emission wavelength for monochromic emission, but they are not effective in realizing a desired Lambertian distribution of the emission intensity. Therefore, optimizing viewing characteristics and even realizing omnidirectional emissions, i.e., not only the peak emission wavelength is independent of the observation angle, but also the emission pattern exhibits ideal Lambertian distributions, is the first-rank solution. In this letter, we present an effective method to resolve the viewing angle dependence of the devices by introducing gratings and filling process into TOLEDs, which can realize gradually changed cavity lengths associated with gradually changed resonant wavelengths. As a result, the disadvantage that the emission peak wavelength of the device will

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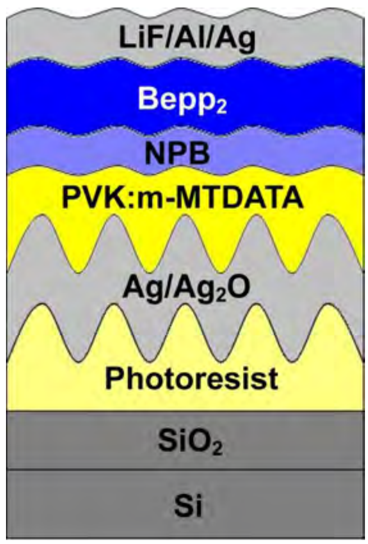

Fig. 1. Schematic of the TOLEDs with gratings.

change with the variation of viewing angles has been eliminated and a Lambertian emitter has been obtained.

3. Results and discussion

The scheme of our devices is shown in Fig. 1. We used Si/SiO_2 as substrates and applied the holographic lithography technique to fabricate gratings of photoresist. The photoresist (NOA63, Norland Products, Inc.) 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) with 3 nm pulse width, 10 ns pulse length, 10 Hz repetition rate and 355 nm wavelength. We chose the period of our gratings to be 2 μm, which should be larger than the visible wavelength scale to avoid disturbing the flat and wide band emission by Bragg scatterings in the visible region [17–21]. A 80 nm-thick Ag film was evaporated as the anode. Then the anode was exposed in UV light for 70 s to obtain a thin film of Ag_2O to enhance the holes injection. Next, a composite layer composed of poly(N-vinyl carbazole) (PVK) and 4,4′,4″-tris (3-methylphenylphe-nylamino) triphenylamine (m-MTDATA) with a ratio of 1:1 by weight was spin-coated on the anode. Tetrahydrofuran (THF) was used as the solvent with 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 (NPB, 8 nm)/$Bepp_2$ (15 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.

As shown in Fig. 1, the depth of the gratings is reduced after spin-coating PVK:m-MTDATA. Therefore, the lengths of the microcavity in the device are not a constant but changed periodically with the fluctuation of gratings [22]. The surface morphology of photoresist, Ag anode, and spin-coating PVK:m-MTDATA layer are shown in Fig. 2, which were measured by Atomic Force Microscope (AFM,

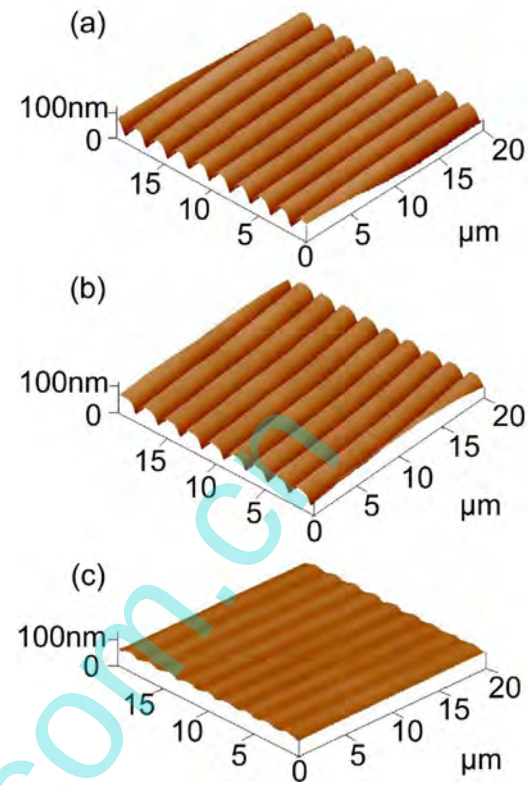

Fig. 2. Atomic Force Microscope figure of (a) surface morphology of photoresist; (b) Ag anode, and (c) spin-coating PVK:m-MTDATA layer.

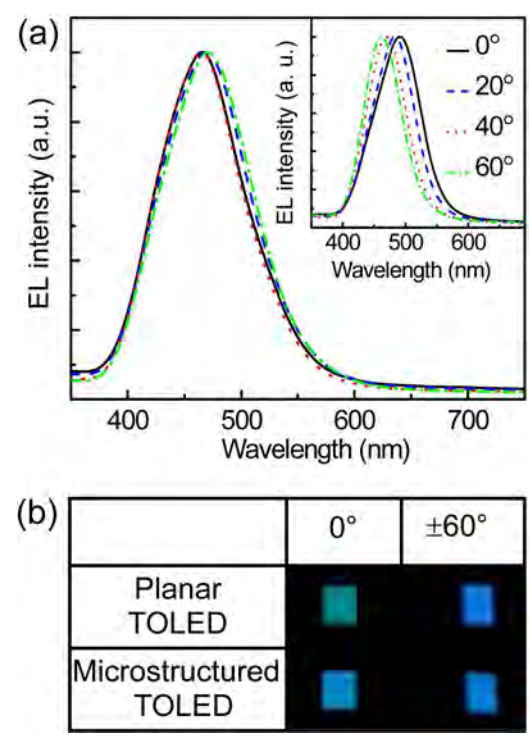

Fig. 3. (a) Normalized electroluminescence spectra of the devices with and without gratings at different viewing angles. (b) Photograph of the planer device and corrugated device at the driving voltage of 5 V with viewing angles of 0° and ±60° (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.).

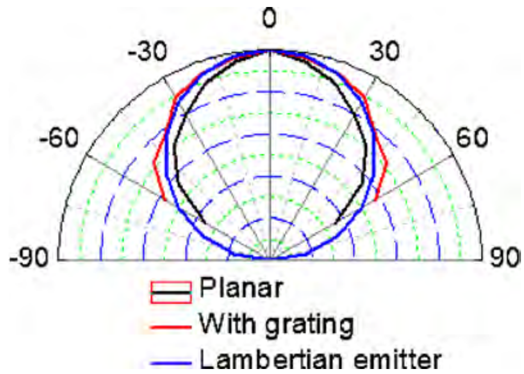

Fig. 4. Polar plots of the emission intensities of devices with and without gratings and the comparison with the Lambertian emitter.

CSPM5000, BenYuan). The grating depths were determined to be 48.7 nm, 48.1 nm, and 10.8 nm, respectively. The surface morphology was duplicated when Ag anode was deposited on photoresist. And the grating was filled and smoothed when PVK:m-MTDATA layer was spin-coated. Therefore, a variation range of ~40 nm for the gradually changed cavity length is obtained after the deposition of the Ag cathode.

The EL spectra of the two kinds of devices at different viewing angles were measured, as shown in Fig. 3a. In the devices with gratings, the emission peaks of the spectra were almost the same with the viewing angles changed from 0° to 60°, while a 30 nm blue shift can be observed for planer devices (see the inset of Fig. 3a). Photos of the operating blue-colored devices with and without gratings were also shown to confirm the superiority of the device with gratings in color stability. As shown in Fig. 3b, a color shift can be observed by the naked eyes for the planar devices. In contrast, the colors of devices with gratings were almost

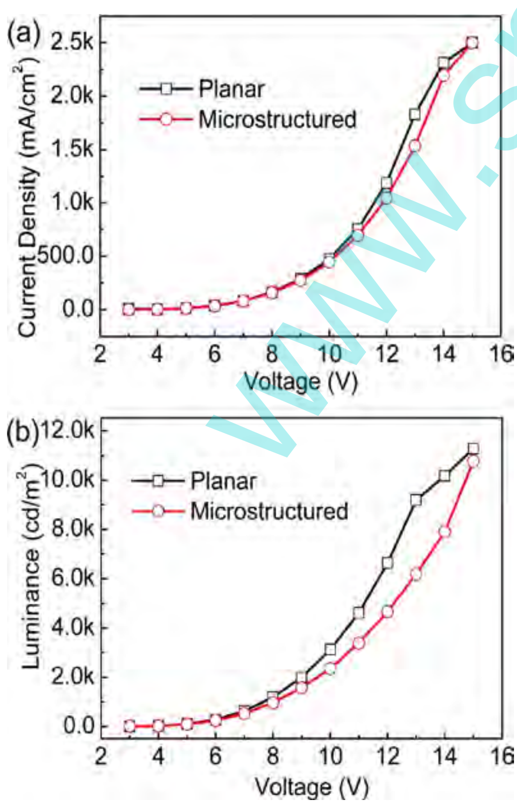

Fig. 5. (a) Current density and (b) luminance–voltage characteristics of TOLEDs without and with gratings.

identical. Then we measured the EL intensity of planar and corrugated devices at different viewing angles and compared them with the Lambertian emitter. As shown in Fig. 4, we can see that compared with planar devices, the performance of the device with gratings was much closer to that of the Lambertian emitter. Especially, the EL intensity of the device with gratings was a little larger than that of the Lambertian emitter at large viewing angles such as 30° and 60°. The EL intensities are decreased to 89.19% and 57.39% at viewing angles of 30° and 60° for TOLEDs with gratings, while these two values are 79.71% and 35.73% for the planar ones.

At last, the current density–voltage and the luminance–voltage characteristics of the TOLEDs with and without gratings are compared in Fig. 5. We find that the planar and corrugated devices exhibit almost identical EL performance, while the maximal luminance is 10,776 cd/m^2 and 11,290 cd/m^2 in TOLEDs for corrugated and planar devices, respectively. These results certify that our method can not only resolve the viewing angle dependence in conventional TOLEDs, but also retain compared EL performance in the corrugated devices.

4. Conclusion

In summary, we have eliminated the angular dependence in TOLEDs caused by the microcavity effect via introducing a microstructured cavity with periodically and gradually changed cavity length. A conventional holographic lithography technique combined with filling process of the groove by spin coating of polymer films has been demonstrated as a simple approach with high controllability and reproducibility to construct the microstructured cavity. The Lambertian emitter has been obtained and the peak emission wavelength of the devices is almost not changed with viewing angles. This is essentially important for the applications of the TOLEDs in both displays and solid-state lightings.

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