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Letter

Roughening the white OLED substrate's surface through sandblasting to improve the external quantum efficiency

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ABSTRACT

A simple, low cost, and scalable process based on sandblasting to modify the OLED substrate's surface, has been successfully developed. The rough surface produced by sandblasting efficiently suppressed the internally generated photons' waveguide mode, and enhanced the white OLED's EQE from 9% to 11.6% without changing the emission spectrum and the Lambertian emitter property. The improvement of the EQE was found to monotonically decrease with the surface roughness within the roughness range from around 1 μm to 3 μm. The white OLED's luminous efficiency was increased from 15.5 cd A^{-1} to 20 cd A^{-1}. Furthermore, the realization of rough surface on a 3.5 inch white lighting panel not only improved the 9-point uniformity from 80% to 90%, but also demonstrated the manufacturing scalability of the sandblasting technique.

1. Introduction

Due to their promising applications in full-color flat-panel displays, backlights for liquid-crystal displays (LCD), and solid-state lighting sources, organic light-emitting diodes (OLED) have attracted considerable interests since their discoveries [1–5]. Through collective efforts by world-wide researchers, and heavy investments by display companies, OLED technology has been commercialized in the display industry in the past decade. Recently, the development of white OLEDs (WOLEDs) for the application in the solid-state lighting became the focus of OLED researches. The power efficiency (PE) of WOLEDs based on small molecules has been reported to reach 90 lm W^{-1} [6], while the PE of WOLEDs based on semiconducting conjugated polymers has exceeded 20 lm W^{-1} [7,8], for the devices without any substrate's surface modifications. Since the internal quantum efficiency almost reached 100% [9–11], how to improve the external quantum efficiency is critical for WOLEDs' success in the lighting industry.

The relationship between the internal quantum efficiency (IQE) defined as the number of generated photons per injected carrier, and the external quantum efficiency (EQE) defined as the number of photons emitted into the viewing direction per injected carrier [12], is expressed in the following equation:

$$\eta_{EQE} = \eta_{IQE} \times \eta_{OUT} \quad (1)$$

where η_{OUT} is the light output coupling efficiency. As schematically illustrated in Fig. 1a, a large portion of internally generated lights can not exit the OLED devices' forward viewing side, due to the total reflection at the interface between the air and the transparent device substrate which generally has a high refraction index value. The light output coupling efficiency determines how much lights can escape from the device in the forward viewing direction. For a smooth plane device surface, the η_{OUT} is given by [13]:

$$\eta_{OUT} = 1 - \frac{3}{4}\left\{\sqrt{1-\frac{1}{n^2}} + \frac{1}{3}\left(1-\frac{1}{n^2}\right)^{\frac{3}{2}}\right\} \approx 0.75n^{-2} \quad (2)$$

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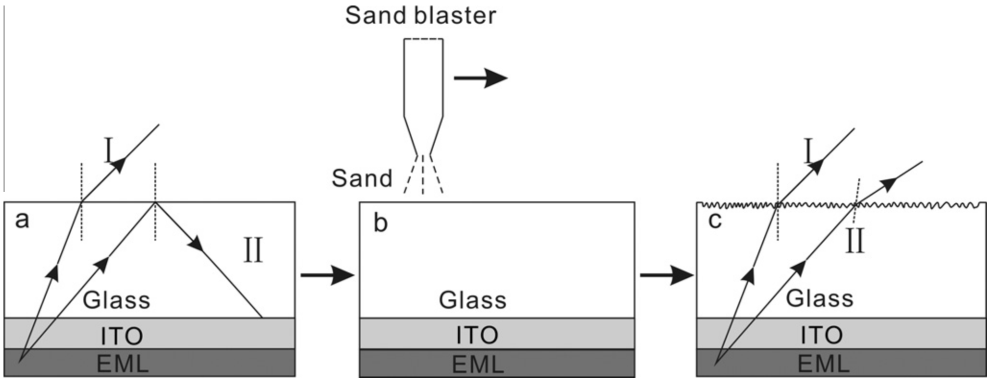

Fig. 1. Schematics of (a) the propagation of lights from an OLED device with smooth surface substrate. I represents the escaped lights, and II represents the trapped lights; (b) sandblasting process; and (c) the propagation of lights from an OLED device with rough surface substrate. Both lights I and II can escape from the OLED surface.

where n is the refraction index of the substrate. Taking the refraction index of the glass ($n \sim 1.5$), the η_{OUT} is only 0.33, meaning that two thirds of the generated lights are trapped inside.

To address the output coupling issue, two directions are generally considered: lowering the substrate's refraction index, or modifying the light's incident angle at the substrate–air interface. Tsutsui's group used silica aerogel with n around 1 as the device substrate to double the EQE [14]. However, the fragility and porosity of the silica aerogel prevents its use in real applications. To modify the light's incident angle, various approaches have been attempted, such as mesa structures [15], spherical substrate [6,16,17], microlens array [18], Bragg grating [19–21], corrugated structures [22–24], textured surface [25,26], and so on. However, all the methods aforementioned required complicated substrate process, including precise photolithography [15,18–23,25,26], lamination [6,16], stamping [18,24], self assembly [17], etc. Moreover, some of the device structures like spherical substrate, or mesa structure are impractical in the application of large area, plane light source. It's clear that a simple, scalable, and low cost process suitable for large size substrate in the industrial manufacturing facility is critical for the success of WOLED as solid-state lighting source.

In our contribution, we developed a novel process to roughen the substrate surface via sandblasting. The sandblasting technique, was first mentioned by Prof. Baldo's group [27], and was realized in a green small moledule OLED by Prof. Kwok's group [28]. The rough surface on OLED device will change the emitted lights' incident angle at the substrate–air interface, leading to more escaped photons in the forward viewing direction as illustrated in Fig. 1(c). By employing the sandblasting method, the maximum brightness of the WOLED was enhanced 42.5%, and the external quantum efficiency was increased 28.9%. Through the accurate control of the surface roughness, we found a linear dependence of the EQE improvement on the surface roughness in the roughness range from around 1 μm to 3 μm. The successful demonstration of the sandblasting technique on a 3.5 inch WOLED lighting panel shows the great potential of such technology in real manufacturing.

2. Experiments

To demonstrate the rough surface effects on the external quantum efficiency, solution processed WOLEDs with the device configuration of ITO/poly(ethylendioxythiophene):poly(styrene sulfonic acid) (PEDOT:PSS)(50 nm)/poly(*N*-vinylcarbazole) (PVK)(40 nm)/light emitting layer (60 nm)/Ba(4 nm)/Al(200 nm) were fabricated. The white light emission was achieved by doping a blue emitting conjugated dendrimer G0 with phosphorescent green emitter $Ir(mppy)_3$, and red emitter $Ir(piq)_2acac$. The blue light device was made with G0 only, while the red and green devices were obtained by doping PVK with $Ir(piq)_2acac$ and $Ir(mppy)_3$, respectively. The molecular structures of the materials and the device structures are detailed in our early publication [29,30]. All chemicals and materials were purchased and used as received. PVK was purchased from Aldrich. $Ir(piq)_2acac$ and $Ir(mppy)_3$ were purchased from American Dyes Sources. PEDOT:PSS was CleviosTM P Al 4083 from H. C. Starck GmbH. G0 was provided by Prof. Jian Pei in Peking University, Beijing, China [29]. Device fabrication followed well-established processes that have been described elsewhere [30]. The current density (J)-voltage (V)-luminance (L) characteristics were obtained using a Keithley 236 source meter and a silicon photodiode calibrated by a Chroma Meter CS-200 (Konica Minolta). The EL spectra and CIE coordinates were recorded by a PR-705 SpectraScan Spectrophotometer (Photo Research). The EQEs were obtained in an integrating sphere (IS-080, Labsphere). To measure the forward viewing EQE, the edges of the devices were covered by the black ink. No lights escaped from the device edges.

Sandblasting is one of the abrasive blasting techniques, which uses high-pressure air to blow a stream of sands against a surface. It's widely used for refurnishing buildings, creating art works, cleaning surfaces, etc. In display industry, as a low cost and scalable process, sandblasting is adopted for making barrier ribs on the rear panel of the plasma display panel. Fig. 2 shows the three dimensional pictures of the glass substrate's surface before and after sandblasting. The glass surface became textured from smooth after sandblasting. To characterize the rough