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Dual pattern for enhancing light extraction efficiency of white organic light-emitting diodes

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ABSTRACT

Nano and micro-patterns (dual patterns) were introduced on a glass substrate as an extraction layer to enhance the light extraction efficiency of white organic light-emitting diodes (WOLEDs). The dual-patterned glass was fabricated by thermal evaporation, direct printing, and reactive ion etching. The combination of nano- and micro-structures imparted highest current density and luminance to the dual-patterned WOLED without electrical degradation. Additionally, the dual-patterned WOLED exhibited higher current and power efficiencies compared to that of the nano- and micro-patterned WOLEDs, which increased by 21% and 27% at 1 mA/cm^2, respectively, as compared to that of the reference.

1. Introduction

Organic light-emitting diodes (OLEDs) are currently used as lighting sources and are intensely researched for high color quality, mercury and UV light-free devices, applicability to flexible substrates, and low power consumption. By consistently researching structures and materials, the internal quantum efficiency of the OLEDs has been improved to nearly 100% [1–3]. However, the external quantum efficiency (EQE) is below 30% because of the confinement of light by glass substrates and waveguide modes (WGMs) of the ITO/glass interface, and the loss of surface plasmon polaritons (SPPs) from the organic layer/metal interface. Thus, low extraction efficiency poses a hindrance to the widespread commercialization of OLEDs.

Various strategies have been reported for the extraction of each confined mode: micro-lens arrays (MLAs) [4,5] and textured surfaces [6,7] to extract the substrate modes; photonic crystals [8–11], low-index grids [12,13], nano-scattering layers [14–17], high refractive indexes [18,19], and moth-eye coatings [20] to extract the WGMs; and applying corrugated structures [21–23] and ensuring greater distances between the emitting layer and the metal and alternate electrodes [24] to minimize SPP loss. The best way to extract a glass-confined mode is to apply a hemispherical lens so that all the incident angles of the rays are within the critical angle range. However, in OLED lightings, the size of the hemispherical lens needs to be increased with increasing light-emitting area, which is impractical. MLAs are mainly used in OLEDs instead of hemispherical lenses and accord high light extraction efficiencies. However, a reduction in the extraction amount due to the finite lens size of the MLA is inevitable, which limits the extraction of all the confined modes.

In this study, we extracted the substrate mode using a dual-pattern structure with nanopillar arrays in the microstructure. The fabrication of the externally patterned OLED via nanoimprint lithography (NIL), which is a low-cost process providing high throughput and high resolution and is applicable to large surfaces up to 6-inch wafer scale, could be advantageous in avoiding the aforementioned issues. Although NIL has been reported for nano and/or micro patterning of substrates, only few of those works reported an enhancement in EQE with or without compromising each optical characteristic of the nano- and micro-structures.

Micro- and dual-structured white OLED (WOLED) has been reported via a direct printing technique of the NIL process using hydrogen silsesquioxane (HSQ) [25–27] and reactive ion etching (RIE) to enhance the EQE. We selected HSQ as light extraction material for patternability and mechanical stability. The dual-patterned WOLEDs exhibited the highest light extraction efficiency compared to the nano- and micro-patterned WOLEDs without a spectrum shift. The current and power efficiencies of the dual-patterned device increased by 21% and 27% at 1 mA/cm^2, respectively.

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2. Experimental

The fabrication process involved three major steps. In the first step, WOLED substrates were prepared by depositing a 100-nm-thick chromium layer on boroaluminosilicate glass slides (Corning Eagle XG™), comprising B_2O_3, Al_2O_3, SiO_2, and Na_2O, via thermal evaporation to fabricate the micro-patterned and nano- and micro-patterned glass substrates. Thereafter, SF6 (MicroChem™), which is a lift-off layer (LOL), was spin-coated at 3000 rpm for 30 s and baked at 170 °C for 4 min. The second step involved the formation of nano, micro, and dual patterns onto the glass substrates. To replicate a micro-cone pattern with a period of 3 μm, diameter of 2.6 μm, and height of 1.5 μm, polydimethylsiloxane (PDMS) was poured into a master stamp and cured at 100 °C for 2 h. PDMS was chosen as the NIL mold material due to its low surface energy and high solvent permeability, which allow easy detachment of the mold from the master stamp and absorb the solvent of HSQ (FOX-16, Dow Corning). After demolding the cured PDMS mold from the master stamp, 17.6 wt% HSQ (MIBK base) was spin-coated on it at a speed of 3000 rpm and acceleration of 1000 rpm/s for 30 s. Afterwards, the prepared substrate was placed onto the HSQ-spin-coated PDMS mold and a pressure of 5 bar was applied for 5 min to transfer the micro-cone pattern onto the LOL through direct printing, during which the PDMS mold was demolded. We chose the direct printing technic to fabricate micro-pattern due to the volume of micro pattern. If the imprint process was performed on the LOL coated substrate instead of direct printing process, the HSQ resin could not fill the micro pattern fully so that the pattern would not be fabricated well. The HSQ residual layer was removed by reactive ion etching (RIE) via CF_4 and O_2 mixed gas in a ratio of 9:1, whereas the LOL was etched by O_2 plasma-based RIE. After dry etching, a residual 100-nm-thick Cr layer was etched via the inductively coupled plasma reactive ion etching (ICP-RIE) process using 50 sccm of Cl_2 gas and 10 sccm of O_2 gas for 10 min at 8 mTorr with 800 W of plasma and 30 W of bias power, as shown in Fig. 1(d). After the lift-off process using an organic solvent, the remaining Cr patterns were used as a mask to etch the glass substrate. Subsequently, ICP-RIE of SiO_x was performed to fabricate micro-patterned glass substrates under the conditions of 6 mTorr pressure, 1600 W plasma power, and 350 W bias power using an etching gas comprising C_4F_8 (80 sccm) and O_2 gas (10 sccm) for 320 s. The etching system used in this study was a MACS-ACE™ from STS. The Cr layer was then removed, and micro-patterned glass (Fig. 2(b)) was obtained via the wet etching process using a buffered oxide etch 6:1 solution (J.T.Baker®) for 1 min, which contains 33.5% ammonium fluoride and 7% hydrofluoric acid. To fabricate a dual-patterned substrate with nano- and micro-sized patterns (Fig. 2(c)), a continuous ICP-RIE process of SiO_x was performed following the steps shown in Fig. 1(f) and (g). A nano-patterned substrate, as shown in Fig. 2(a), was fabricated by ICP-RIE of a bare boroaluminosilicate glass slide under the same conditions

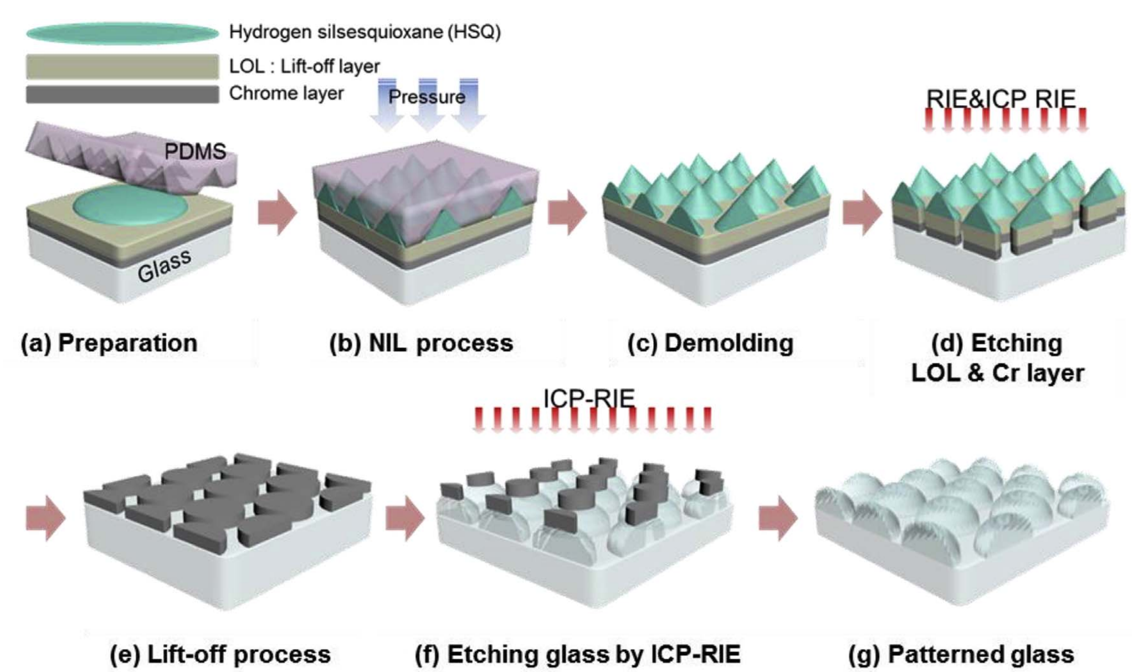

Fig. 1. Fabrication process of dual-patterned substrate.

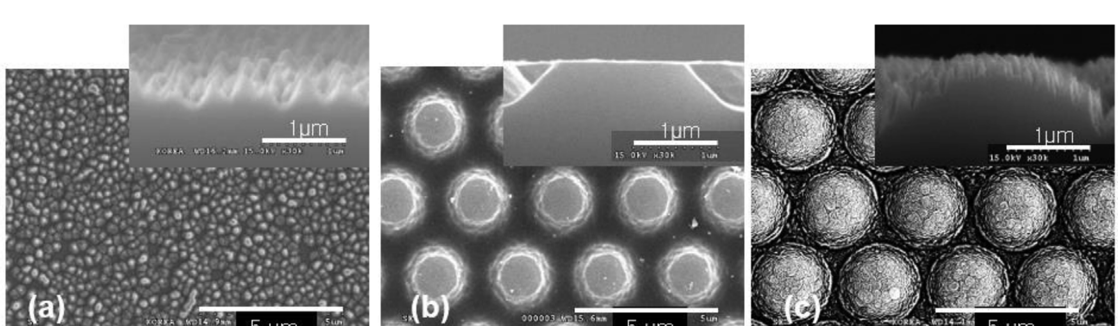

Fig. 2. FE-SEM images of nano (a), micro (b), and dual structures (c).