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Fabrication and implementation of large-area organic light-emitting-diode devices on direct patterned backplanes

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ABSTRACT

In this paper, we report on a new cost-effective fabrication technology for large-area organic light-emitting diode (OLED) devices that we have developed. We fabricated OLED lighting devices on a directly patterned backplane using a dry process without employing conventional photolithography patterning technology. The indium–tin-oxide (ITO) anode, metal cathode, insulator, and emissive organic layer patterns were all formed directly on the substrates during the sputtering and evaporation steps by using a shadow mask without using etching or lift-off methods. We fabricated and characterized green phosphorescent emission OLED devices with an emission area of 30 × 120 mm^2, based on backplanes formed by direct patterning technology. Application of direct patterning technology reduced the total number of processing steps to 4 from the 26 steps required by conventional photo-patterning technology, making it possible to reduce large-scale production cost. Although the process steps were reduced considerably, the typical characteristics were comparable to those of photo-patterned OLEDs. Furthermore, the lifetime of the OLEDs based on direct patterned backplane was observed to be 27,200 h, which is approximately 97% of the lifetime of conventionally patterned OLEDs.

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1. Introduction

Organic light-emitting diodes (OLEDs) have attracted significant attention for use in flat panel displays and solid-state lighting because of their unique properties such as vivid full color, low power consumption, fast response time, and extendibility to flexible displays [1–6]. Especially, OLED lighting is considered to be leading a paradigm shift in the solid-state lighting industry by virtue of its salient characteristics such as surface emission, transparency, and flexibility [7–15]. Over the decades, the typical characteristics of OLED lighting devices have improved substantially resulting in higher luminance, higher current efficiency, and longer lifetime [16–18].

One of the major hurdles in the commercialization of OLED lighting systems is their relatively high price as compared to bulbs and fluorescent lamps because of the large equipment investment, complex manufacturing process, and high mass production cost. Although OLED lighting devices have the potential to be used as next-generation solid-state lighting with light-emitting diodes, they still suffer from price competitiveness. Thus, to replace bulbs and fluorescent lamps with OLED lighting in general lighting, the biggest challenge is to reduce large scale production cost. Therefore, commercialization of OLEDs requires new cost-effective fabrication technology.

In general, in OLED lighting device fabrication, patterns are formed by using a conventional photolithography system with wet or dry etching during the anode, auxiliary electrode, and insulator patterning steps. Although the photolithography patterning technology is mature and provides accurate resolution, it involves several processing steps: photoresist coating, soft baking, exposure, developing, hard baking, etching or lift-off, and photoresist removal. The large equipment required to implement these relatively complicated processing steps of the conventional photolithography system results in high production costs. Moreover, the wet process involved in the OLED fabrication steps is not preferred since active emissive organic materials are vulnerable to water vapor in the backplane. Thus, dry processes, which do not involve exposure to water or solution, are preferred for stable performance and longer lifetimes.

On the other hand, direct patterning technology using a shadow mask does not involve complicated processing steps requiring large equipment investment. Since patterns can be formed simultaneously during thin film deposition in the preparation of transparent anode, auxiliary electrode, and insulator layers without the

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use of photolithography and etching processes, the number of steps are considerably reduced. This reduces the cost of mass production. Therefore, direct patterning technology can be used as an alternative to conventional photolithography patterning technology for manufacturing low-cost OLED devices.

During the fabrication of the OLEDs, patterns in the active organic emission layer and metal cathode were formed directly using shadow mask. However, the direct patterning technology was not used to form patterns in the anode and insulator layer because the surface morphology and shape were not suitable to obtain performance comparable to photo-patterned OLEDs.

In this paper, we report on the fabrication of OLEDs based on a directly patterned backplane consisting of ITO anode and insulator layers. All the patterns on the OLEDs were formed directly on the substrates during the deposition of each thin-film in a single process. The surface morphology of the directly patterned layer was modified by post-treatment to improve the performance of the OLEDs and the shapes were also strictly controlled. OLEDs, based on directly patterned backplane, with emission area of 30 × 120 mm^2 were fabricated and characterized. Photo-patterned OLEDs were also fabricated and characterized for reference. The current density (J)—luminance (L)—voltage(V) characteristics and lifetimes were compared to the characteristics and lifetimes of photo-patterned OLEDs.

2. Experimental details

Before the patterns were formed directly on the glass substrates, the 200 × 200 mm^2 sized glass substrates (Eagle 2000) were subjected to cleaning using acetone, isopropyl alcohol, and deionized water. Because there are no additional cleaning processes, this initial cleaning step to remove particles such as organic debris and dust is very important. The presence of these particles can cause short circuits. This is because the thickness of the active emissive organic layer becomes thinner along the sidewall of the particles due to the poor step coverage of the thermal evaporation system.

A 150 nm thick ITO anode layer was deposited and patterned simultaneously during the RF sputtering step by using a shadow mask. The base pressure was 5.5×10^{-7} torr. During the sputtering step, the working pressure was maintained at 2 mtorr with an Ar flow rate of 200 sccm and RF power of 300 W. To obtain a low sheet resistance for the as-sputtered ITO layers, the temperature of the substrate was fixed at 250 °C. During the direct patterning of ITO by sputtering, spike-like structures can form on the ITO layer due to electromagnetic wave interference between the plasma zone and metal shadow mask [19]. Since these spike-like structures are relatively tall compared with the active organic and metal cathode layers, these structures induce high current density locally resulting in heat generation owing to current crowding. These locally heated regions are often called hot spots. In large-area OLED devices, hot spots might pose a serious problem. Therefore, spike-like structures need to be removed by post-treatment. We used thermal and plasma treatments to remove the spike-like structures and smoothen the surface of the directly patterned ITO layer. The thermal treatment was performed using a rapid thermal annealing system for 1 h at a temperature of 380 °C. The thermal treatment temperature was chosen such that it does not induce thermal damage in the ITO-coated glass substrates. The oxygen plasma treatment was performed after the heat treatment was completed. The RF power and oxygen flow rate were 150 W and 50 sccm, respectively. The working pressure was 20 mTorr and the oxygen plasma treatment time was 180 s. The detailed process flow and results of the surface treatment of shadow-mask-patterned ITO anode layer have been reported in another work [20].

To separate the anode and metal cathode layers, an insulator layer was prepared using direct patterning technology same as used for the ITO anode layer patterning step. For the insulator material, a polymethylmethacrylate (PMMA) polymer-based organic material was used. Flash evaporation, followed by UV curing was used to prepare the PMMA-based insulator material, and its thicknesses was fixed at 1000 nm.

When patterns are formed directly on substrates by using a shadow mask, the gap between the shadow mask and the substrates should be minimized to prevent the occurrence of an unexpected long shadow tail with a gentle slope. The shadow tail results in an unwanted area that cannot contribute to emission, and a leakage current with a large magnitude that negatively impacts the electrical and optical characteristics of OLED lighting devices. Moreover, to reduce the unwanted shadow tail area, slope of the shadow tail was also controlled. We maintained the gap at less than 5 mm during the sputtering and evaporation steps to minimize the shadow effect. Thus, the backplane consisting of direct patterned ITO and insulator layers was fabricated by using direct patterning technology via a dry process without employing the conventional photolithography system and wet chemical processes.

To evaluate the properties of direct patterned backplanes, phosphorescent green OLED lighting devices were fabricated and their electrical and optical properties were analyzed. The emission areas of the OLED devices were 4 × 4 and 30 × 120 mm^2. The phosphorescent green OLED lighting devices consisted of a 10 nm thick LG-101 as hole injection layer (HIL), 25 nm thick 4,40-bis[N-(1-nathyl)-N-phenylamino] biphenyl (NPB) as hole transport layer (HTL), 25 nm thick 4,40-N,N0-dicarbazolylbiphenyl (CBP) doped with tris(2-phenylpyridinate) iridium(III) ($Ir(ppy)_3$, 8 wt.%) as emitting layer (EML), 10 nm thick m-bis(triphenylsilyl) benzene (UGH3) as hole/exciton blocking layer (HBL), 30 nm thick (2,9-dimethyl-4,7-diphenyl-1,10-phenanthroline) (Bphen) as electron transport layer (ETL), 1 nm thick lithium fluoride (LiF) as electron injection layer (EIL), and 100 nm thick aluminum (Al). Conventional glass encapsulation technology was used for encapsulation. The surface roughness and images of the direct patterned backplane were analyzed by atomic force microscopy (AFM: PSI XE-200) and with a field emission scanning electron microscope (FE-SEM: Quanta 200 FEG). The electroluminescence spectra, J—V—L characteristics, and leakage current were analyzed using Keithley 2400, 2100 semiconductor parameter analyzer, and CS-2000.

3. Results and discussion

Fig. 1(a) shows a schematic of the direct patterning technology employing the shadow mask equipped sputtering process proposed in this study. By using a shadow mask, the ITO and insulator layers were patterned simultaneously during deposition on glass substrates in a single step. The alignment was carried out using CCD camera and the align margin was 50 μm during the anode and insulator direct patterning steps. Because the ITO and insulator patterns were formed directly on the glass substrates during the deposition steps without employing conventional photolithography patterning technology, the resolution of the directly patterned layer may be very low. Since fine patterns with a resolution of 1 μm, that are generally employed in active matrix OLED displays are not required in OLED lighting devices, the aligning accuracy we used is sufficient for the use of direct patterning technology in mass production of low-cost OLED lighting panels.

The complete process flow for the fabrication steps of OLED lighting devices fabricated using l direct patterning technology is depicted in Fig. 1(b). In general, an organic layer and metal cathode layer are deposited and patterned using the direct technology. However, in our case, the ITO anode layer and insulator layer were also deposited and patterned using a direct patterning technology to achieve simplicity in the fabrication process and lower

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