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Full color organic light emitting diodes with laser-patterned optical path-length compensation layer

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ABSTRACT

In this paper, we describe a promising way to fabricate micro-cavity OLEDs (organic light emitting diodes) with the concept of "super top emission" with soluble optical path-length compensation layer (OPCL) formed by Laser Induced Thermal Imaging (LITI) technology. OPCL is an additional layer for setting the cavity length corresponding to intrinsic wavelength of emitter. The resultant OLEDs gave a saturated three primary colors (RGB) after transmitting through common color filters by micro-cavity effect. By this approach, we could simplify the fabrication process of full color OLEDs by reducing conventional color patterning step, fine metal mask method. We also suggested the blending system of polymer and small molecule as transfer layer and this could improve the quality of laser patterning by controlling the surface energy adequately. Also, this system could be a solution to LITI problem of chronic contaminant because transferred materials could remain after cleaning process. Devices fabricated by soluble/LITI process showed comparable or even better performances and the device characteristics could enhance by further study of optimizing several parameters such as materials property and laser patterning condition. Also, we expect that this concept could lead to develop the fabrication process of large and high-resolution OLED displays.

1. Introduction

In the past decade, significant breakthroughs in organic light emitting diodes (OLED) technology have been achieved and this makes the commercialization of OLED displays very successful. The OLED has been expected to be applicable to next-generation displays such as transparent and flexible display and considerably progressed by many research groups. Nevertheless, some serious drawbacks still exist on the path of realization of large-area and high-resolution displays. This results mainly from fine metal mask (FMM) method which is current sole mass production technology for active-matrix OLEDs (AMOLEDs). This patterning method has been considered as a poor color patterning technology with a low accuracy (±10–12.5 μm) compared to the conventional photolithography process [1,2]. Nevertheless, as photolithography process requires the use of wet etchant, developer, stripper, etc., all of which can damage organic layers, there has been no other better option than using such FMM method for patterning pixels [3–8]. Recently, the Laser Induced Thermal Imaging (LITI) process has been suggested as the most promising alternative technology, because it yields a much higher patterning accuracy (abou ±3 μm) and is applicable to large-area AMOLED display fabrication [9].

Meanwhile, white OLED with color filter is another option to prepare high-resolution as well as large area displays. Especially, the "super top emission" technology reported by Kashiwabara et al. has been considered to realize the characteristic features such as smart shape and superior image quality and ultra-high resolution AMOLED

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aiming to achieve full color display ranging from mobile applications to televisions [10,11]. In fact, this approach normally requires complicated reflective indium tin oxide (ITO) anode fabrication process to adjust the total thickness of OLED for specific micro-cavity length precisely. Thus, Chen et al. recently reported the modified anode fabrication process by applying very thin insulating layer to improve the process yield [12]. In this study, they separate the ITO from the anode, that is, they used ITO as an optical path-length compensation layer (OPCL). On this wise, "super top emission" structure is very attractive because it gives many advantages as follows: (i) improved power consumption because there is no need to use polarizer film which impedes extracting light in forward direction, (ii) improved contrast ratio due to its unique structure which can realize saturated three primary colors, and (iii) improved yield in OLED fabrication because of elimination of color patterning step by using shadow mask.

Furthermore, we could enhance the efficiency of OLEDs by applying top emission structure because the micro-cavity effect could be realized by interference occurred within a reflective anode and a semi-transparent cathode. The peak wavelength of emission spectra will be affected by the intrinsic color of emitter and the resonance wavelength which is determined by the Fabry–Perot condition as follows:

$$2m\pi = \sum_i \frac{4\pi d_i n_i(\lambda)}{\lambda} - \varphi_{\text{cathode}}(0,\lambda) - \varphi_{\text{anode}}(0,\lambda)$$

where λ is the emission wavelength of emitter, $\varphi_{\text{cathode}}(0,\lambda)$ and $\varphi_{\text{anode}}(0,\lambda)$ are the angle- and wavelength-dependent phase changes on reflection from top cathode and the bottom anode, respectively, m is an integer that defines the mode number, and $n_i(\lambda)$ and d_i are the refractive index and the thickness of the ith organic layer [13]. With the optimal thickness of the micro-cavity, interference occurs between the light emitted and reflected at the reflective anode in OLED which leads to enhancement of light emission. Micro-cavity OLED with color filters also contributes to an increase in the contrast ratio by suppressing reflection of incident ambient light compared to a conventional panel with a circular polarizer [11].

In this study, we report a novel technology using the concept of soluble organic OPCL formed by LITI process in the conventional small molecular OLED structure.

2. Experimental

2.1. Materials

Soluble materials blended by 4, 4′, 4″-*tris*-(*N*-(naphthylen-2-yl)-*N*-phenylamine)triphenylamine (2-TNATA) and poly[(9,9-dioctylfluorenyl-2,7-diyl)-co-(4,4′-(*N*-(4-s-butylphenyl)diphenylamine)] (TFB) in a 3:1 ratio was utilized as an OPCL. Glass transition temperatures (T_g) of 2-TNATA and TFB were 112.4 and 156 °C, respectively. 4,4′-Cyclohexylidene*bis*[*N*,*N*-*bis*(4-methylphenyl)benzenamine] (TAPC) was used as a hole transport layer (HTL). 2,6-*bis*(3-(carbazol-9-yl)phenyl)pyridine (26DCzPPy) was used as a host material for emission layer (EML). As dopant materials in EML, *bis*(3,5-difluoro-2-(2-pyridyl)phenyl(2-carboxypyridyl) iridium(III) (FIrpic), *tris*(2-phenylpyridine) iridium ($Ir(ppy)_3$), *bis*(2-phenylquinoline)(acetylacetonate) iridium(III) ($Ir(2\text{-}phq)_2(acac)$) were used for blue, green, and red emission, respectively. 1,3,5-*Tri*[(3-pyridyl)-phen-3-yl]benzene (TmPyPB) was used as an electron transport layer (ETL). And, lithium fluoride (LiF) and magnesium (Mg) doped with silver (Ag) were used as an electron injection layer (EIL) and cathode, respectively. All the materials were purchased from commercial suppliers and used without purification.

2.2. Device fabrication

ITO/Ag/ITO anode with 9 mm^2 of active area with aperture ratio of 9.03 and/or 42.7% was formed by photolithography process. The substrate was cleaned by sonication in acetone and isopropyl alcohol, rinsed in deionized water, and finally irradiated in a UV-ozone chamber. Both OPCL and HTL were stacked on these UV-O_3 treated ITO substrates. All the cavity lengths corresponding to three primary colors were optimized by simple calculation through SimOLED. We obtained the optical path lengths for primary colors at the fixed ETL thickness condition because we just wanted to vary the HTL thickness which could be formed by LITI process. The proposed thickness of OPCL resulted from such optical simulation was 19 nm and 50 nm for green and red, respectively. To form these optimized thicknesses of OPCL, we controlled the concentration of 2-TNATA:TFB solution (e.g. 0.5 wt% for green and 1.5 wt% for red). The solution was spin-coated on the specially fabricated donor film at 1000 rpm for 30 s and the layers were transferred to the substrate by LITI process. The LITI condition was varied according to the thickness of OPCL; the optimized energy dose for green was 1.7 J/cm^2 (15 W, 200 mm/s) and the red OPCL was transferred clearly at 2.3 J/cm^2 (20 W, 200 mm/s). After this process, stable phosphorescent white OLED based on a double emissive layer was formed by evaporation process and the structure is referred to Ref. [15]. All organic materials were deposited by the vacuum evaporation technique under a pressure of $\sim 1 \times 10^{-7}$ Torr. The deposition rate of organic layers was about 0.5 Å/s. LiF and Mg:Ag were deposited with rates of 0.1 Å/s and 3 Å/s, respectively. The structure of full color OLED device and energy level are shown in Fig. 1(b). Color filters were simply fabricated previously by photolithography process.

2.3. Measurements

The current density–voltage (J–V) and luminance-voltage (L–V) data of OLEDs were measured by Keithley 2635A and Minolta CS-100A, respectively. The OLED area was 9 mm^2 (with aperture ratio of 9.03% and 42.7%) for all the samples studied in this work. Electroluminescence (EL) spectra, CIE coordinates and external quantum efficiencies were obtained using a Minolta CS-2000 spectroradiometer.