



Colored reflective organic light-emitting device without bias



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ABSTRACT

Under white ambient illumination and without bias, a reflective organic light-emitting device (ROLED) comprising a microcavity cathode exhibited various colors for static information display applications by means of internal interference and absorption effects. The configuration of this microcavity cathode was a metal/organometallic/metal structure of Al (10 nm)/Ag (15 nm)/Ag nanoparticles doped inside tris(8-hydroxyquinolino) aluminum (Alq₃) (x nm)/Al (100 nm) with excellent conductivity. The thickness of the Ag:Alq₃ played a crucial role in determining the reflection color; for example, varying it from 20, 40, 60, 80 and 100 nm yielded the colors light yellow, light orange, reddish purple, greenish blue, and light green, respectively. In the dark, this ROLED can be used to display information with an ultra-high contrast ratio by applying on a small bias, like conventional OLED displays. Hence, this ROLED is a highly promising candidate for applications in energy-saving electronic fixed-pattern signs, logos, indicators, and manual information displays.

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1. Introduction

Information displays are ubiquitous in modern life, e.g. various size displays as indicator boards, billboards and placards are used by millions of people use to obtain, share, and communicate the information. Such displays can be classified into irradiative and nonradiative apparatus. Generally, most irradiative displays show clear information in the dark, but require high power consumption to avoid information washout under bright ambient light (e.g., direct sunlight). Conversely, nonradiative billboards or placards painted using the highly reflective materials show clear information under bright ambient light, but require the auxiliary lamps mounted nearby for displaying information in the dark, which means yet another source of high power consumption. Several approaches have been studied to ameliorate the washout problem in irradiative displays, including the use of polarizer lamination or a black background to reduce reflection [1–3]. Another

possibility is to raise the driving power to increase the brightness of the displays; however, in this case, concerns regarding energy wastage and the degradation of the device's lifetime inevitably arise [4,5].

In this study, we used organic light-emitting devices (OLEDs), a type of irradiative display, for constructing an energy-saving information display with no washout under strong illumination. The numerous advantages of using OLEDs include self-emission, low power consumption, and an easy fabrication processes [6–8]. To date, several reports have expounded on the improved readability and amelioration of washout under strong illumination by substantially reducing the reflection by means such as front polarizer lamination [1], intraabsorptive organic layer [9], absorptive cathode [3,10–13], and low reflection cavity cathode [14–19]. Such designs entail a drastic increase in the contrast ratio (CR) of the display by using a black background. We also reported a promising development whereby an absorptive and conductive cavity cathode, fabricated with an interlayer of N,N'-bis(2,6-diisopropylphenyl)-1,7-bis(4-methoxy-phenyl)perylene-3,4,9,10-tetracarboxydiimide (MPPDI), a highly absorptive organic

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material with outstanding electron transport properties, was used to attain a low average reflectance of 1.39% across the entire visible band and obtain a bone fide black background [20]. Nonetheless, even using the aforementioned low reflection OLEDs, one is still unable to sidestep the issue of the greater energy wastage necessary for boosting the luminance under direct sunlight illumination to avoid washout.

Hence, we designed a colored reflective OLED (ROLED) for application in information displays to simultaneously resolve washout and energy wastage problems. The mechanism for colored reflection is embedded within the ROLED and controlled by the cavity cathode. Compared with the structure of our previous low reflection OLED, the modification here involved replacing the MPPDI with a highly transparent organic material, tris(8-hydroxyquinolino)aluminum (Alq₃), to achieve the desired band reflection. In addition, various reflective colors can be achieved by adjusting the thickness of the interlayer within this cavity cathode. Patterning these ROLEDs as an information display yields zero power consumption under bright conditions, and displays information with an ultra-high CR in the dark by applying on a small bias.

2. Experiment

To realize the colored ROLEDs, we modified the cathode design of the traditional structure of bottom emission green fluorescent OLEDs. In the beginning of the device fabrication process, a precleaned patterned indium tin oxide (ITO) substrate was used as the anode and surficially treated using oxygen plasma to raise its work function from 4.9 eV to 5.1 eV. Next, this ITO substrate was transferred into a multisource evaporator to sequentially grow the hole transport layer, 60 nm of N,N'-biphenyl-N,N'-bis(1-naphthyl)-1,1'-biphenyl-4,4'-diamine (NPB), emitting layer and electron transporting layer, 60 nm of Alq₃ under an ultrahigh vacuum of below 5×10^{-6} torr. We then replaced the shadow mask to deposit electron injection layer, 1.2 nm of LiF, and a microcavity cathode structure, which was composed of a front semitransparent bilayer aluminum/silver (Al/Ag) electrode, a highly conductive interlayer (Alq₃:Ag with a volume ratio of 10:1), and a rear thick Al layer. Their thicknesses were 2.5 (Al), 7.5 (Ag), x (Alq₃:Ag), and 100 (Al) nm, where x is a variable. The first thin Al layer functioned to improve the electron injection efficiency by affiliating a metal with the LiF [21]. The ensuing 7.5-nm thin Ag layer was used to ensure the high transparency and excellent conductivity of the front electrode [3,22,23]. The detailed configurations of these colored ROLEDs are shown in Table 1. These devices were thoroughly encapsulated with a glass cover under ultra-violet (UV) curing in a glove box (N₂ level was approximately 99.95%). The electrical and optical characteristics of these devices, such as the current density versus driving voltage (J - V), luminance versus driving voltage (L - V), and current efficiency versus current density (cd/A- J) were measured using an LJV system consisting of a multisource meter (Keithely 2400) and a spectrometer (Minolta CS1000). The reflection spectra of the OLEDs were obtained by using

a spectrometer (Hitachi U4100), and the refractive index and absorption coefficient of the single thin film were measured using an ellipsometer (Raditech SE-950).

3. Results and discussions

We present one control OLED device and two ROLED groups with various cathode structures as shown in Table 1. The control OLED device (D1) possessed a traditional NPB/Alq₃ OLED structure with a highly reflective Al cathode. The first group of ROLED devices (D2–D6) possessed a microcavity cathode design with an Alq₃:Ag interlayer of various thicknesses (20, 40, 60, 80, 100 nm); the second group of ROLED devices (D7–D9) was designed without microcavity cathode because the front semitransparent Al/Ag layer was removed for the comparison with the D2–D4 devices. Their J - V characteristics are shown in Fig. 1. Naturally, these three types of OLEDs exhibited three types of electrical behavior. The control device D1 exhibited the most satisfactory electrical properties, with a driving voltage of 7.11 V at 100 mA/cm². The driving voltage increased when the conventionally thick Al cathode was replaced with the colored reflective cathode, ranging from 7.64 to 7.79 V at 100 mA/cm². The colored ROLED D2 exhibited a small lag in the driving voltage of 0.53 V at 100 mA/cm² behind that of the control device D1 because the conductivity of the conventional thick Al cathode was greater than that of the microcavity cathode with a 20-nm Alq₃:Ag interlayer. However, the first group of devices, D2–D6, exhibited approximately identical J - V curves, with only an insignificant shift of only 0.15 V at 100 mA/cm². This indicated that the microcavity cathodes with Alq₃:Ag interlayers of increasing thickness from 20 to 100 nm contributed to the approximately identical conductivities. This also demonstrated the excellent conductivity of Alq₃:Ag, which translated into the insensitivity of the J - V performance of the OLEDs with the microcavity cathodes to the increasing thickness of the Alq₃:Ag interlayer.

The second group of devices, D7–D9, exhibited poor electrical performance, with their driving voltages lagging behind those of devices D2–D4 by at least 3 V at 100 mA/cm² because these device lacks the front semitransparent Al/Ag conductive layer. Despite the good conductivity of the rear Alq₃:Ag/Al cathode, electron injection into the emitting layer Alq₃ remained difficult because the LiF/Al pair dominated the electron injection from the cathode into the organic material. In addition, the Alq₃:Ag layer was merely conductor-like and was not a perfect conductor. Nonetheless, the increasing thickness of the Alq₃:Ag layer still contributed to the gradually increasing resistance to enervate the electron transport from the rear Al cathode to the emitting layer, and the diminishing electrical field inside the OLED slowed the carrier mobility of the organic layer. Hence, D7, the device with the thinnest Alq₃:Ag layer in this group, exhibited electrical performance superior to that of the other two devices. Comparing the device performances between these two groups revealed that the first front semitransparent Al/Ag layer is a crucial structure underpinning the electrical performance of the colored ROLEDs.

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