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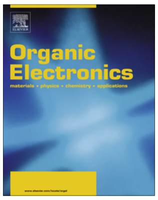

Improved out-coupling efficiency of organic light emitting diodes by manipulation of optical cavity length

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ABSTRACT

The relationship between thickness of electron transport layer (ETL) and device performance of organic light-emitting diodes (OLEDs) was investigated. Especially, we prepared various OLEDs by varying the thickness of ETL to investigate the difference of device performance. Very interestingly, the device efficiency of green phosphorescent organic light emitting diodes (PHOLEDs) was significantly improved when the thickness of ETL was optimized even though we did not change any materials for such devices except that we applied highly conductive Li doped ETL. This means that the only one factor which is associated with an improvement of device efficiency could be originated from the constructive optical interference. As a result, the simple modification of PHOLEDs only by changing the optical thickness condition causes a dramatic improvement of current efficiency (up to 82.4 cd/A) as well as external quantum efficiency (EQE, up to 23.8%), respectively. Those values correspond to the much more improved ones (by ~34.4%) compared to those obtained from the normal devices with thin ETL as a reference.

1. Introduction

Phosphorescent organic light-emitting diodes (PHOLEDs) have attracted intense interest because of their merit of high quantum efficiency as compared to conventional fluorescent OLEDs through utilizing both singlet and triplet excitons for emission [1–4]. As a result, green and red phosphorescent materials have been applied in the main-display of commercial mobile phones since 2013 [10]. However, compared with red phosphorescent materials, green components have still many problems because it shows relatively shorter lifetime than red components. To overcome such issue, the modification of PHOLEDs by changing the composition of emitting layer (EML) through mixed host approach [5,6] and/or bipolar host approach has been broadly investigated [7,8]. In addition, the adjustment of relative current density (e.g. $J_{hole}/J_{electron}$: hole current density/electron current density) of EML has also become an important issue to improve a device lifetime [9,10]. As a part of such an effort, the efficiency greater than 20% (EQE, external quantum efficiency) was frequently reported from the green PHOLEDs with such kinds host materials [11]. Nevertheless, there is still a lot of potential for improvement the EQE of OLEDs because they are strongly affected by the out-coupling factor as shown in the following equation:

$$\eta_{EQE} = \gamma \times \eta_{S/T} \times q_{PL} \times \eta_{out} \qquad (1)$$

where γ is the charge balance factor, $\eta_{S/T}$ is singlet–triplet factor, q_{PL} is photoluminescence quantum yield (PLQY), and η_{out} is out-coupling efficiency of the emitted light [12]. In principle, we cannot obtain the external quantum efficiency greater than 20% even if γ, $\eta_{S/T}$, and q_{PL} are nearly 100% because η_{out} cannot reach over 20% in conventional OLEDs [13].

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Thus, many research groups have focused on improvement of the out-coupling efficiency by using the additional films with special morphology such as micro-lens array or by embedding a certain nanostructure in between glass substrate and electrodes so that they change the direction of internally wave-guided beam to outside [14–16]. However, they were hardly applicable to the display application due to a pixel blur effect of such functional films. Hence, most of the panel makers such as Samsung, LG, etc. producing the AMOLEDs is utilizing a strong microcavity effect by using Purcell effect to enhance an out-coupling efficiency [16–18]. From these methods, however, we cannot utilize an intrinsic optical characteristics merely originated from the emitter itself. In other words, spectral change of electroluminescence (EL) at specific wavelength or non-Lambertian emission pattern is inevitable from such out-coupling methods [19,20]. Thus, the ideal way is to maximize a device efficiency without any change of peculiar quality of EML itself.

In this paper, we investigated the method relating to the cavity effect for improving efficiency of bottom emission OLEDs which are known as non-cavity devices. The cavity enhancement factor in OLEDs, $G_{\text{cav}}(\lambda)$, is given by [21,22]:

$$G_{\text{cav}}(\lambda) = f_{\text{FP}}(\lambda) \times f_{\text{TI}}(\lambda; z_o) \tag{2}$$

with

$$f_{\text{FP}} = \frac{T_{\text{anode}}}{\left(1 - \sqrt{R_a R_c}\right)^2 + 4\sqrt{R_a R_c}\sin\left(\frac{\Delta\varphi}{2}\right)} \tag{3}$$

$$f_{\text{TI}} = 1 + R_c + 2\sqrt{R_c}\cos\left(-\varphi_c + \frac{4\pi n_{\text{org}} z_0 \cos(\theta_{\text{org,EML}})}{\lambda}\right) \tag{4}$$

$$\Delta\varphi = -\varphi_a - \varphi_c + \sum_{i_{\text{th}}} \frac{4\pi n_i d_i \cos(\theta_i)}{\lambda} \tag{5}$$

where $f_{\text{FP}}(\lambda)$ and $f_{\text{TI}}(\lambda)$ are Fabry–Perot and two-beam interference factors, respectively. A z_o is the distance between dipole of emitter and reflective cathode. R_a and R_c mean the reflectance values at the anode–organic and cathode–organic interfaces, respectively. $\Delta\varphi$ is the round-trip phase parameter, and φ_a and φ_c are phase changes which occur upon reflections at the anode–organic interface and cathode–organic interface, respectively. n_i and d_i are refractive index and thickness of i_{th} organic layer.

In conventional OLEDs with transparent anode and reflective cathode, cavity effect are almost related with $f_{\text{TI}}(\lambda;\, z_o)$ because the value of R_a was nearly zero. In other words, device performance could be affected by changing electron transport layer (ETL) thickness which can determine the value of z_o. Indeed, many research groups report the optimum thickness of ETL with optically satisfying constructive interference [23–25]. However, since the thickness for enhancing efficiency is so thick that charge balance of device could be disrupted, the charge balance of such devices could be deteriorated [26]. Thus, we studied on how to maintain the charge balance of devices by changing the ETL part to an n-type doped one because the ideal thickness of ETL based on optical simulation is too thick to give highly efficient device characteristics. Besides, we investigated how n-doped ETL affects to electric characteristic. In addition, the proper thickness of n-doped ETL in total thickness of ETL was investigated to enhance the much more efficient device characteristics by good charge balancing in our devices fabricated.

2. Experiment

2.1. Materials

We used indium tin oxide (ITO) as an anode, *N,N′*-Bis(naphthalen-1-yl)-*N,N′*-bis(phenyl)benzidine (NPB) and 4,4′,4″-tris(carbazol-9-yl)-triphenylamine (TCTA) as a hole transport layer (HTL). Beryllium bis(2-(2′-hydroxyphenyl)pyridine) (Bepp_2) and *fac*-tris(2-phenylpyridinato)iridium(III) [Ir(ppy)_3] as host and dopant materials for EML. 4,7-diphenyl-1,10-phenanthroline (Bphen) was used for an undoped ETL and a layer of Bphen doped with Lithium (Li) formed n-doped ETL (n-ETL). Materials for electron injection layer (EIL) and cathode were lithium fluoride (LiF) and aluminum (Al).

2.2. Device fabrication

ITO anode with 4 mm^2 of active area 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. All organic materials were deposited by the vacuum evaporation technique under a pressure of $\sim 5 \times 10^{-7}$ Torr. The deposition rate of organic layers was about 0.5–1 Å/s. Li, LiF and Al were deposited with rate 0.08 Å/s, 0.1 Å/s and 3 Å/s under $\sim 10^{-6}$ Torr, respectively.

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. Electroluminescence (EL) spectra and the Commission Internationale De'Eclairage (CIE) coordinate were obtained using a Minolta CS-2000A spectroradiometer.

3. Results and discussion

3.1. Optical simulation

The thickness of ETL of the green OLED devices [ITO (150 nm)/NPB (30 nm)/TCTA (10 nm)/Bepp_2:Ir(ppy)_3 (1.5%, 20 nm)/Bphen (*x* nm)/LiF (1.5 nm)/Al (100 nm)] for achieving constructive interference at wavelength of 510 nm was calculated by optical mode analysis as shown in Fig. 1. From the result, we obtained the thickness of ETL for green PHOLEDs at the fixed other layer thickness condition because we just vary ETL thickness. We assumed that the recombination zone was located at center of EML. From the simulation result, we found that there are two optimal condition to obtain fairly high EQE if we select the ETL thickness of 70 nm or 250 nm. The maximum possible