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Journal of Luminescence

journal homepage: www.elsevier.com/locate/jlumin

Blue and white phosphorescent organic light emitting diode performance improvement by confining electrons and holes inside double emitting layers

Yu-Sheng Tsai^{*}, Lin-Ann Hong, Fuh-Shyang Juang, Cheng-Yin Chen

Institute of Electro-Optical and Materials Science, National Formosa University, Yunlin 63201, Taiwan, ROC
Institute of Electro-Optical and Materials Science, National Formosa University Yunlin63201Taiwan, ROC

ARTICLE INFO

Article history:

Received 15 August 2013

Received in revised form

7 March 2014

Accepted 20 March 2014

Available online 28 March 2014

Keywords:

Complex emitting layer

Recombination rate

Confine

Outcoupling enhancement film

ABSTRACT

In this research, complex emitting layers (EML) were fabricated using TCTA doping hole-transport material in the front half of a bipolar 26DCzPPy as well as PPT doping electron-transport material in the back half of 26DCzPPy. Blue dopant Flrpic was also mixed inside the complex emitting layer to produce a highly efficient blue phosphorescent organic light emitting diode (OLED). The hole and electron injection and carrier recombination rate were effectively increased. The fabricated complex emitting layers exhibited current efficiency of 42 cd/A and power efficiency of 30 lm/W when the luminance was 1000 cd/m², driving voltage was 4.4 V, and current density was 2.4 mA/cm². A white OLED component was then manufactured by doping red dopant [Os(bpftz)₂(PPh₂Me)₂] (Os) in proper locations. When the Os dopant was doped in between the complex emitting layers, excitons were effectively confined within, increasing the recombination rate and therefore reducing the color shift. The resulting Commission Internationale de L'Eclairage (CIE) coordinates shifted from 4 to 10 V ($\Delta x = -0.04$, $\Delta y = +0.01$). The component had a current efficiency of 35.7 cd/A, a power efficiency of 24 lm/W, driving voltage of 4.6 V and a CIE_{x,y} of (0.31,0.35) at a luminance of 1000 cd/m², with a maximum luminance of 15,600 cd/m² at 10 V. Attaching an outcoupling enhancement film was applied to increase the luminance efficiency to 30 lm/W.

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1. Introduction

There are two popular ways to fabricate a white OLED: mixing blue/yellow light and mixing blue/green/red light. For lighting fixtures the peak luminance efficiency is observed at a luminance of 1000 cd/m² and the color coordinates need to match lighting standards. Increasing the luminance efficiency of OLED components is the trend for the future. In the paper by Su et al. [1], a double light emitting layer structure was proposed, that combined hole-transport materials with a bipolar host, and red dopant placed in between the two light emitting layers. The resulting high efficiency, high stability white phosphorescent component had a color shift from 100 to 1000 cd/m², and the CIE differences $\Delta x = -0.06$, $\Delta y = 0.00$. Lee et al. proposed a hybrid light emitting layer architecture consisting of both hole-transport and electron-transport materials [2–4], which effectively reduced the energy gap between the hole transport layer and light emitting layer and lowered the driving voltage. Lee et al. employed double emission layers into blue phosphorescent OLEDs with a power efficiency

of 21 lm/W under luminance of 1000 cd/m² [7]. Dong et al. used DBTTF4 as a single host, achieving two-color based white PHOLEDs from cold white emission with CIE coordinate of (0.31, 0.43), current efficiency 34.9 cd/A, and power efficiency 16.9 lm/W at 1000 cd/m² [9]. Liu et al. used those two phosphorescent materials with a pure ultrathin yellow light-emitting layer ((t-bt)₂Ir(acac)) and a doping blue light-emitting layer. The current efficiency and power efficiency of 79 cd/A (at 1550 cd/m²) and 40.5 lm/W (at 1000 cd/m²), and CIE coordinate (0.32, 0.38) were obtained [10]. Koo et al. achieved an appropriate deep blue phosphorescent host (TPSBN) by doping only one orange phosphorescent emitter, (Bz4Fppy)₂Ir(III) acac. The optimized WOLED showed a maximum luminous efficiency of 22.38 cd/A, a maximum power efficiency of 12.01 lm/W, and CIE coordinate of (0.38, 0.42) at 500 cd/m² [11]. Piao et al. combined fluorescent (DOPPP) and phosphorescent (POAPF) blue emitters and ultrathin yellow phosphorescent dye of PO-01 to fabricate white OLEDs. At the practical brightness of 1000 cd/m², the current efficiency was 30.4 cd/m², power efficiency was 28.3 lm/W and CIE coordinate of (0.40, 0.44) [12]. Son et al. reported color stable phosphorescent white OLEDs based on a double emissive layer structure composed of blue and red/green phosphorescent units. The white OLED showed a current efficiency

^{*} Corresponding author.

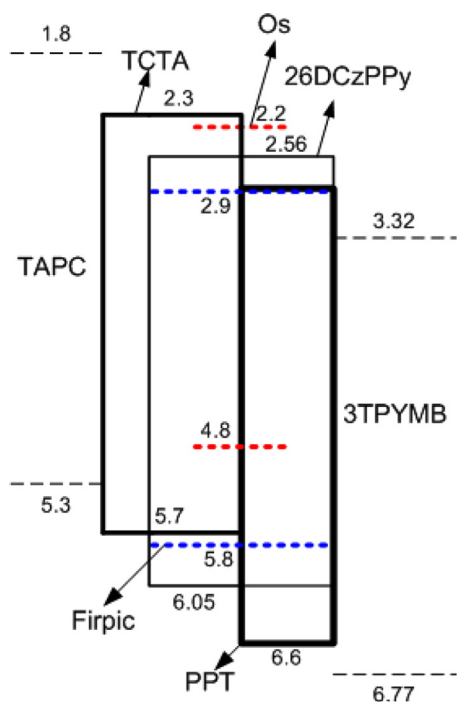


Fig. 1. Structure diagram of white phosphorescent OLED.

of 46.4 cd/A, power efficiency of 38.7 lm/W at 1000 cd/m², and the color coordinate change of (−0.002, +0.002) from 1000 cd/m² to 5000 cd/m² [13].

This paper presents a structure with the goal of confining electrons and holes. A white phosphorescent OLED was fabricated using complex bipolar double emitting layers with both lower LUMO (lowest unoccupied molecule orbital) and higher HOMO (highest occupied molecule orbital) materials. Electrons and holes within the light emitting layers were controlled by doping three main light emitting materials and the electronics and luminance properties of the component were studied. Component tuning was focused on increasing the power efficiency and lowering the driving voltage. Red dopant was also used to produce high efficiency white phosphorescent OLEDs with better Commission Internationale de L'Eclairage (CIE) stability.

2. Experiment

This research began with improving blue phosphorescent OLED component efficiency by adjusting the main light emitting layer structures to reduce the energy gap and driving voltage. Indium tin oxide (ITO) patterned glass with $13.59 \pm 5 \Omega/\text{Sq}$ of resistance was used as the substrate. The substrate was cleaned using acetone, isopropyl alcohol and de-ionized water followed by oxygen plasma treatment. All organic and metal layers were prepared under the pressure of 6.65×10^{-4} Pa via thermal evaporation. The layers were processed in the following order: hole transport material 1,1-bis[(di-4-tolylamino) phenyl]cyclohexane (TAPC), which had lower HOMO energy level (5.3 eV) and hole mobility rate $\mu_h \sim 10^{-2}$ cm²/Vs; hole transport host or buffer layer 4,4',4''-tris(N-carbazolyl) triphenylamine (TCTA) [5], which had a better hole mobility rate $\mu_h \sim 10^{-4}$ cm²/Vs; bipolar host 2,6-bis(3-(carbazol-9-yl)pyridine) (26DCzPPy) (μ_h, μ_e about 10^{-5} cm²/Vs) [1,5,8]; and 2,8-bis(diphenylphosphoryl) dibenzothiophene (PPT) that had deep HOMO level (6.6 eV) and electron transport host [7]. The host layers were mixed in 1:1 ratio. Guest blue phosphorescent dopant iridium(III)bis((4,6-difluorophenyl)-pyridinate-N,

C20)picolate (Firpic) was doped simultaneously at a concentration of 20%, and electron transport layer tris[3-(3-pyridyl)-mesityl] borane (3TPYMB) its electron mobility ($\mu_e \sim 10^{-5}$ cm²/Vs) [6]. The sample was then placed in a metal evaporation chamber with cesium fluoride (CsF)/aluminum (Al) deposited under pressure of 6.65×10^{-4} Pa using as the cathode. The resulting component area was 25 mm². Its properties were measured under normal atmosphere. The luminance intensity and spectrum were measured using SpectraScan PR-650. Keithley 2400 served as both the power supply and measurement equipment for current–voltage characteristics.

3. Results and discussion

Different component structures were explored in this research as listed in Table 1. and Fig. 1. The base structure was ITO/TAPC/TCTA/EML/3TPYMB/CsF/Al, and the EML construction was controlled to find the best component efficiency. Device A had a single co-dopant EML made by mixing identical TCTA and 26DCzPPy. In order to lower the HOMO energy gap of 0.75 eV between the hole transport (TAPC) and light emitting layers (26DCzPPy), TCTA, a light emitting material with good hole transport characteristics was inserted in between. TCTA has high triplet energy (E_T) level of 2.82 eV and can effectively intercept excitons from 26DCzPPy ($E_T=2.71$ eV) and Firpic ($E_T=2.62$ eV). Moreover, as a buffer layer TCTA has a lower hole mobility rate ($\mu_h \sim 1.0 \times 10^{-2}$ cm²/Vs) than TAPC ($\mu_h \sim 1.0 \times 10^{-4}$ cm²/Vs), which in turn effectively balances the hole injection rate quantity. Because TCTA HOMO is 5.7 eV, the energy gap for holes transporting from TAPC to 26DCzPPy is reduced, implying better hole injection capability. However, TCTA/26DCzPPy as one layer results in higher energy gap between itself and 3TPYMB for electrons in LUMO of electron transport layer, which makes electron injection more difficult under low driving voltage. As a result, the driving voltage of Device A is on the higher end and it is not easy to improve the device efficiency. Device A had power efficiency of 15.6 lm/W at luminance of 1000 cd/m² and driving voltage of 4.9 V, as shown in Table 2. The EML structure was further tuned to improve the component efficiency. Device B used a double light emitting layer structure. Two light emitting layers were used: TCTA in the front half to reduce hole injection energy barrier, and 26DCzPPy in the back half to reduce electron injection energy barrier between TCTA and 3TPYMB. When the luminance was 1000 cd/m², Device B had a lower driving current density (3.4 mA/cm² vs. 4.1 mA/cm²) and higher current efficiency (29.8 cd/A vs. 24.4 cd/A) compared to Device A, according to the data in Table 2. The results show that the double light emitting layer material properties can effectively improve the hole and electron injection.

The front half of the EML of Device C was a blend of 26DCzPPy and TCTA. While a bipolarity of 26DCzPPy is behind the EML. Using bipolar 26DCzPPy electron–hole mobility (μ_h, μ_e about 10^{-5} cm²/Vs) control the front half EML (26DCzPPy:TCTA) electron and hole current. To improve the hole and electron transport in 26DCzPPy:TCTA so that carrier recombination area will be located at the center of double EMLs, and the effective recombination area will increase to improve the luminance efficiency. When the luminance was 1000 cd/m², the driving voltage of Device C lowered from 4.8 to 4.4 V, current density increased from 3.4 mA/cm² to 3.6 mA/cm², and power efficiency improved from 19.5 lm/W to 20 lm/W. The 26DCzPPy:TCTA blend increases both the hole and electron currents without confining them inside the EMLs. The excess current loss makes little luminance efficiency improvement. The I - V - L curve shown in Fig. 2 also demonstrates this fact. However, it also reveals that the luminance is significantly higher, which indicates that 26DCzPPy

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