

Improved the power efficiency of white phosphorescent organic light-emitting diode with thin double emitting-layers and hole-trapping mechanism

Fuh-Shyang Juang^{1,*}, Shun-Hsi Wang¹, Yu-Sheng Tsai¹, Ming-Hong Gao¹, Yun Chi², and Han-Ping, Shieh³

¹ Institute of Electro-Optical and Materials Science, National Formosa University, Yunlin, 632, Taiwan
Phone: +886-5-631-5029 E-mail: fsjuang@seed.net.tw

²Department of Chemistry, National Tsing Hua University, Hsinchu, 300, Taiwan

³Department of Photonics & Display Institute, National Chiao Tung University, Hsinchu, 300, Taiwan

1. Introduction

Recent reported on structures which can improve efficiency of organic light-emitting diode (OLED) have been continuously made, e.g. one emitting layer is inserted in heterogeneous interface of devices to increase luminance efficiency [1]. Other literatures also validate that hole-buffer layers can be used to effectively help hole injection, and reduce driving voltage of devices and improve power efficiency [2]. Additionally, compared with single-emitting layer, double-emitting layers can effectively expand exciton-formation zone and reduce efficiency roll-off [3-4]. Because triplet-triplet annihilation is in proportion to triplet exciton density in respect of squares, utilizing thinner emitting layer (EML) can increase triplet exciton density inside EML, and improve influence of triplet-triplet annihilation on devices [5]. Therefore, this study will insert TCTA between hole transport layer (HTL) and EML [6] for adjusting hole currents and improving charge carrier balance, and further increase devices efficiency. Also, white phosphorescent organic light-emitting diode (PHOLED) is made by co-doping orange phosphorescent dopant into ultra thin blue double EMLs [7].

2. Experimental

White PHOLEDs were fabricated on pre-patterned ITO substrates with a sheet resistance of $13.59 \pm 5 \Omega/\text{square}$. The substrates were cleaned via acetone, isopropyl alcohol, DI water followed by O_2 plasma treatment. All organic and metal layers were vacuum deposited under 2×10^{-6} Torr. 1,1-bis[(di-4-tolylamino) phenyl] cyclohexane (TAPC) used as hole transport layer, 4,4',4''-tris(N-carbazolyl) triphenylamine (TCTA) [3] used as hole-buffer layer and hole transport-type host, 2,6-bis(3-carbazol-9-yl) phenylpyridine (26DCzPPy) used as bipolar host, iridium-bis-(4,6-(difluorophenyl-pyridinato-N,C2) (FIRpic) used as blue dopant, doped with 10 wt% of $(\text{Os}(\text{bpftz})_2(\text{PPh}_2\text{Me})_2)$ used as the red dopant, and $\text{ris}[3-(3\text{-pyridyl})\text{-mesityl}]\text{borane}$ (3TPYMB) [8] used as the ETL. The cathode consisted of 0.5 nm thick LiF followed by 200 nm thick Al. Figure 1 shows the Energy band structure of white device with doped $(\text{Os}(\text{bpftz})_2(\text{PPh}_2\text{Me})_2)$ into the double-EMLs interface. Spectra Scan PR650 and Keithley 2400 were employed to measure the current-voltage-luminance (I-V-L) characteristics.

3. Results and discussion

Devices 1 of blue PHOLED in this study is made of ITO/ TAPC (50nm)/ 8wt% FIRpic : TCTA (5nm)/ 8wt% FIRpic:26DCzPPy (5nm)/ 3TPYMB (35nm)/ LiF/ Al. Because there is a excessively large gap in hole mobility between hole transmission layer (TAPC) ($\mu_{\text{h}} \sim 1.0 \times 10^{-2} \text{ cm}^2/\text{Vs}$) and electrical transmission layer (3TPYMB) ($\mu_{\text{h}} \sim 10^{-5} \text{ cm}^2/\text{Vs}$), leading to extreme unbalance in carriers, this study inserts a hole buffer layer between HTL (TAPC) and EML instead of partial TAPC. Structure of Devices 2 is made up of ITO/ TAPC (45nm)/ TCTA (5nm)/ 8wt% FIRpic:TCTA (5nm)/ 8wt% FIRpic:26DCzPPy (5nm)/ 3TPYMB (35nm)/ LiF/ Al. It can be seen from Fig. 1 Luminance-current density and Fig. 2 Power efficiency-current density curves that after inserted a hole buffer layer (TCTA), current density of Devices 2 will be less than that of Devices 1 without inserted buffer layer at a luminance of 1000 cd/m^2 , thus it increases luminance efficiency of devices (see Table I). Because hole mobility of TCTA buffer layer ($\mu_{\text{h}} \sim 10^{-4} \text{ cm}^2/\text{Vs}$) is less than hole transmission material (TAPC). Therefore, TCTA was inserted to control the injection amount of holes from HTL to EML and improve the balance of charge carrier. Experiment results show that when TCTA is used as buffer layer, luminance efficiency of blue device increases up to 12.5 cd/A at a luminance of 1000 cd/m^2 and power efficiency reaches 8.5 lm/W and driving voltage reduces to 4.8 V .

Furthermore, this study also utilizes double emitting layers (D-EMLs) structure to enlarged exciton-formation zone of devices for the purpose of reducing thickness of EML and driving voltage for blue PHOLEDs. In experiment, TCTA and 26DCzPPY are used as host material of D-EMLs, however, FIRpic is a well-know electron transport-type blue dopant, TCTA is a hole transport-type host material and 26DCzPPY is a bipolar transport-type host material. Therefore, through utilizing the difference on transport capability of materials in D-EMLs, in combination with doping concentration of FIRpic, recombination zone will be controlled to be at interface between TCTA and 26DCzPPY [7]. Finally, $(\text{Os}(\text{bpftz})_2(\text{PPh}_2\text{Me})_2)$ is doped in interface between two blue EMLs, thickness of each organize layer of devices are adjusted to be optimal, thus white device with high efficiency will be obtained with its structure (Device 3) being made up of ITO/ TAPC (35nm)/ TCTA (15nm)/ 8wt% FIRpic:TCTA (4nm)/ 1wt% Os:8wt% FIRpic:TCTA (1nm)/ 1wt% Os:8wt% FIRpic:26DCzPPy (1nm)/ 8wt% FIRpic:26DCzPPy (5nm)/ 3TPYMB (30nm)/

LiF/ Al. Figure 3 shows the energy band structure of optimal white device. Because Os can trap hole (with high-lying HOMO level) on interface between two EMLs, recombination zone of devices will be confined to be at interface between two EMLs. It not only enlarges exciton-formation zone and increases devices efficiency (see Fig. 2), but also reduces color shift caused by driving voltage changes of devices. However, it can be seen from Fig. 4 normalized electro-luminescence (EL) spectra of white device under different voltages, intensity of red wavelength will gradually reduce, which is caused by the decreased of transferring energy from FIrpic to Os when driving current density increases [9], leading to blue shift. Based on results of above experiments, luminance efficiency of white device will reach 23.5 cd/A at a luminance of 1000 cd/m², power efficiency will reach 17.5 lm/W and driving voltage reduces to 4.4 V (see Table I). The maximum power efficiency 19.2 lm/W will be reached (at 4V).

No	color	buffer layer	at 1000 cd/m ²			
			V (V)	I (mA/m ²)	Y (cd/A)	P (lm/W)
Device 1	blue	No	5.6	15	6.7	3.8
Device 2	blue	Yes	4.8	8.3	12.5	8.5
Device 3	white	Yes	4.4	5	23.5	17.5

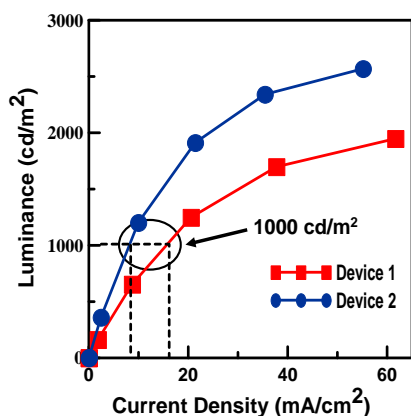


Fig. 1. Luminance –current density curves for blue devices with and without hole-buffer layer (TCTA).

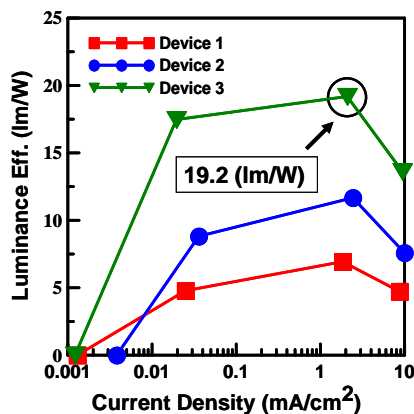


Fig. 2. Power efficiency –current density curves for different devices.

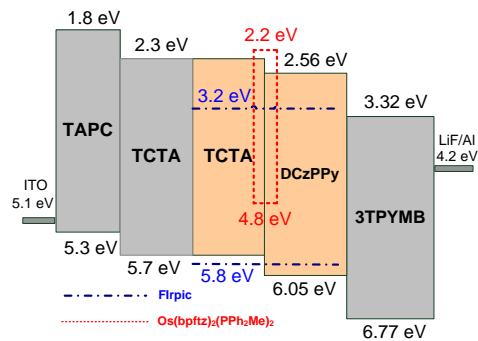


Fig. 3. Energy band structure of white PHOLED.

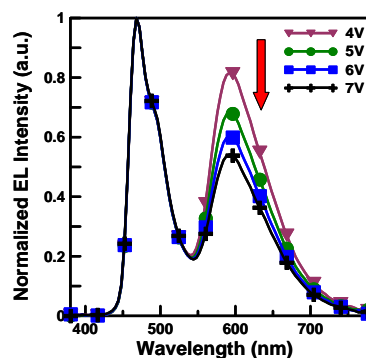


Fig. 4. Normalized electro-luminescence (EL) spectra of white device under different driving voltages.

3. Conclusions

Through host material (TCTA) featuring hole transport-type as buffer layer is inserted by this study, the quantity of holes injected into EML will be effectively controlled, and the balance of charge carrier are realized. Then through expanding recombination zone of devices by using structures of double EMLs, red phosphorescent dopant (Os(bpftz)₂(PPh₂Me)₂) featuring hole trap is co-doped on interface (FIrpic : TCTA/FIrpic : DCzPPy), adjusting thickness of each organic layer to be optimal, white PHOLED with high efficiency will be obtained. When luminance of white devices is 1000 cd/m², driving voltage will reduce to 4.4 V and luminance efficiency will reach 23.5 cd/A and power efficiency increase up to 17.5 lm/W.

Acknowledgements

The authors thank Dr. Mei-Rurng Tseng and Meng-Ting Lee of Industrial Technology Research Institute, Taiwan for valuable discussions. This work was supported by the National Science Council of the Republic of China under NSC -98-2221-E-150-008-.

References

- [1] C. W. Tang, *et. al.*, *J. Appl. Phys.*, **65** (1989) 3610.
- [2] H. You, *et. al.*, *J. Appl. Phys.*, **101** (2007) 026105.
- [3] G. He, *et. al.*, *Appl. Phys. Lett.*, **85** (2004) 3911.
- [4] S. Watanabe, *et. al.*, *J. Photo. Sci. Technol.*, **18** (2005) 83.
- [5] R. G. Kepler, *et. al.*, *Phys. Rev. Lett.*, **10** (1963) 400.
- [6] Qi Wang, *et. al.*, *Appl. Phys. Lett.*, **94** (2009) 103503.
- [7] S. J. Su, *et. al.*, *Adv. Mater.*, **20** (2008) 4189.
- [8] N. Chopra, *et. al.*, *International Meeting on Information Display* (2009) 184.
- [9] C.-H. Chang, *et. al.*, *The SID International Symposium, Seminar and Exhibition* (2007) 1172.