

Efficient and color stable phosphorescent White Organic light emitting devices using ultra wide band gap host materials

Jonghee Lee, Jeong-Ik Lee, Ki-Im Song, Su Jin Lee and Hye Yong Chu*
 Convergence Components & Materials Research Laboratory, Electronics and Telecommunications Research Institute, Daejeon, 305-350, Republic of Korea
 Phone: +82-42-860-6876 , E-mail: clrpaper@etri.re.kr

Keywords : White OLED, Lighting, power efficacy

Abstract

We developed phosphorescent white OLEDs with high efficiency and color stability. By engineering device architecture in which confined excitons within the emissive layer by using adequate interlayer and balanced recombination of charge carriers by using stepwise hole transporting layer system, these WOLEDs showed power efficacy of 43.6 lm/W with CRI = 62 and 36 lm/W with CRI = 72 at 100 cd/m² without outcoupling enhancements.

1. Introduction

White organic light-emitting devices (WOLEDs) for lighting applications have actively investigated over the last few decades since their power efficiencies have surpassed those of incandescent bulbs.¹ WOLEDs make attractive candidates for future solid state lighting sources due to the several reasons, including the low operating voltages, high power efficiencies, and the suitability for processing on flexible substrates.²

WOLEDs for solid state lighting applications require high efficiency, high color rendering index, and appropriate color temperature.³ Many architectures for developing white OLEDs have been reported, such as multi-EML structure doped with different color emitting dopants, use of excimer or exciplex formed by one or two dopants, stacked several OLEDs, down conversion of blue OLEDs, and doping of several dopants in a single emitting layer.⁴ Among them, single EML enables lower operating voltage and color stability because it prevents mismatches of energy levels in multiple EMLs, and therefore, higher power efficacy could be obtained.

There are various methods for high efficient OLEDs, in particular, phosphorescent OLED (PHOLEDs) are most effective way to meet the requirements of high efficiency due to their ability to efficiently utilize both singlet and triplet excitons.^{5,6} Efficient PHOLEDs with 100 % internal quantum efficiency and a high power efficiency of 77 lm/W have been reported

particularly for green and red PHOLEDs. Electron blocking layers and exciton blocking layer have been used between the HTL and the emission layer (EML) in green PHOLEDs. A stepwise doping structure and a double EML structure have also been reported. Although efficient green and red PHOLEDs with excellent performance have been developed, challenges remain in the development of blue and white OLEDs because they require wider band gap materials for both host and dopant than the case for green or red PHOLEDs.

In this work, we reported highly efficient phosphorescent blue and white OLED with using adequate interlayers as a key property to reduce triplet exciton quenching and block charge carrier within the EML. Moreover, we clarified that stepwise hole transporting system reduced the hole injection barrier from the hole transporting layer (HTL) to the emissive layer (EML) and thus power efficacy of WOLEDs were enhanced together with lowering driving voltage. Finally, high power efficacy WOLEDs were developed with 43.6 lm/W, 36.0 lm/W at 100 cd/m² without out-coupling enhancement and CRIs of those are 62, 72, respectively.

2. Experimental

A series of organic light-emitting devices in the current study were made using the configuration: indium tin oxide (ITO)/NPB/mCP/EML/Bphen/LiF (1 nm)/Al (120 nm). (see Fig. 1) ITO was cleaned by the standard oxygen plasma treatment. 4,4'-bis[N-(1-naphthyl)-N-phenyl-amino] biphenyl (NPB), and bathocuproine (2,9-dimethyl-4,7-diphenyl-1,10-phenanthroline) (Bphen) were used as a hole injection layer, a hole-transporting layer (HTL), and an electron transporting layer (ETL), respectively. Blue light emitting iridium(III)bis(4,6-difluorophenyl)pyridinato-*N,C*^{2'} picolinate (Firpic) and/or an orange

phosphorescent emitter, bis(2-phenylbenzothiazolato-*N,C*^{2'})iridium (III)(acetylacetonate) (Bt₂Ir(acac)) was doped in a wide band gap host m-bis-(triphenylsilyl)benzene (UGH3)⁷.

The OLED grade materials were purchased and used without further purification. All organic layers were deposited in a high vacuum chamber below 5×10^{-7} torr and thin films of LiF and Al were deposited as a cathode electrode. The OLEDs were transferred directly from vacuum into an inert environment glove-box, where they were encapsulated using a UV-curable epoxy, and a glass cap with a moisture getter. The electroluminescence spectrum was measured using a Minolta CS-1000. The current-voltage (*I-V*) and luminescence-voltage (*L-V*) characteristics were measured with a current/voltage source/measure unit (Keithley 238) and a Minolta CS-100.

3. Results and discussion

The electroluminescence (EL) spectra and power efficacy versus brightness profiles of blue OLED-Device A and white OLED-Device B is shown in Fig 2. Recently, we have demonstrated that the electroluminescence efficiencies of blue organic light-emitting diodes can be significantly enhanced by the incorporation of interlayers at the hole transporting layer (HTL)/emitting layer (EML) and/or EML/electron transporting layer (ETL) interfaces.⁸ The hole-transporting wide band gap materials were introduced between the HTL and the EML as interlayers in order to block triplet exciton quenching and reduce electron overflow. The effects of adding a second undoped UGH3 interlayer at the EML/ETL interface were also studied. When the appropriate interlayers were added, the device performances were found to be dramatically enhanced, with peak external quantum and power efficiencies of 18.4% and 27.6 lm/W. (Device A)

Based on above results, we developed white organic light-emitting diodes (WOLEDs) by introduction of additional orange light emitting dopant-Bt₂Ir(acac) into device A. (Device B) As shown in Fig 2, by incorporation and optimization of blue and orange light emitting dopants ratio, we obtained WOLEDs with peak external efficiency and power efficacy up to (16.0 % EQE, 33.7 lm/W) without light out-coupling technique. At the practical brightness of 100 cd/m², the performance achieved was 15.0 % EQE, 26.6 lm/W with CIE = (0.39, 0.45).

To obtain highly efficient white OLEDs, especially

achieving high power efficacy, it is desirable that driving voltage of WOLED is lowered. To address this requirement, we introduced stepwise HTL system between the NPB and the mCP of our WOLED-Device B. As shown in Fig 3, observing the energy level diagrams for the materials used in this study, we easily find that there is big difference of HOMO energy levels of the NPB (5.4 eV) and the mCP (6.1 eV). This huge barrier for hole injection (0.7 eV) could increase the driving voltage of WOLEDs. To alleviate this HOMO energy difference for easier hole injection from the anode to the EML, we introduced TcTa layer which has HOMO energy level of 5.7 eV at the NPB/mCP interface. (Device C)

As shown in Fig 4, current density of the TcTa layer incorporated devices highly increased and therefore driving voltage of those also reduced compared to device B which has no TcTa layer. The driving voltage of device B, device C1, device C2, and device C3 at 1000 cd/m² reduced consequently and were 5.6, 5.0, 5.2, and 4.9 V, respectively. Moreover, this effective hole injection and reduced driving voltage also enhanced the external quantum efficiencies (not shown here) and the power efficacies. (See Fig 4-(b)) We have examined the hole injection properties of TcTa layer introduced device C by studying hole only devices. The structures of hole only device are ITO/NPB (x nm)/TcTa (y nm)/mCP (60 nm)/Al (HD1 : x = 40, y = 0; HD 2 : x = 30, y = 10; HD 3 : x = 20, y = 20; HD 4 : x = 0, y = 40) and the results are shown in Fig. 5 The detailed mechanism of device C will be discussed in the presentation.

By device optimization and introduction of TcTa layers, we controlled charge carrier injection/transport rate and reduced driving voltage of our WOLEDs. Especially, device C1 which has a stepwise HTL of the NPB (30 nm)/TcTa (10 nm)/mCP (7.5 nm) showed the efficiencies of 17.6 % EQE, and 36.5 lm/W with CIE = (0.42, 0.47) at 100 cd/m² without outcoupling enhancement. This value is over 35 % enhanced power efficacy compared to that of device B. We also found that this WOLED system exhibited little change of color coordinate from 100 to 10,000 cd/m², giving CIE coordinates from (0.42, 0.47) to (0.40, 0.46), ($\Delta x = 0.02$, $\Delta y = 0.01$).

Although the performances of our WOLEDs dramatically increased, it is still need to improve OLED performances and color rendering index (CRI). Actually, the CRI of device C1 is around 63 which is inferior to actual lighting applications. Accordingly, we have tested new ETL materials which has higher electron mobility than that of Bphen for high

efficiency (Device D) and also introduced deep red dopant into the mCP layer for improved CRI (Device E). Device E was fabricated using the structure of : ITO/NPB(30 nm)/TcTa (10 nm)/mCP:red dopant (5%, 2.5 nm)/mCP (5 nm)/UGH3:Firpic 14%: Bt₂Ir(acac) 0.3% (170 nm)/ETL (50 nm)/LiF (1 nm)/Al (120 nm).

Finally, we reported that the power efficacies of device D and E are 43.6 lm/W, 36.0 lm/W at 100 cd/m² without out-coupling enhancement and CRI of those are 62, 72, respectively. With outcoupling enhancements, the total power efficacy increased to 74.1 lm/W and 61.2 lm/W.⁹

Table I. Device characteristics of WOLEDs in this study

Device	At 100 cd/m ²		
	EQE (%) ^a	P.E. (lm/W) ^b	CRI ^c
B	15.0	26.6	65
C1	17.6	37.5	63
D	17.6	43.6	62
E	17.2	36.0	72

a) EQE is External Quantum Efficiency. b) P.E. is power efficiency. c) CRI is color rendering index.

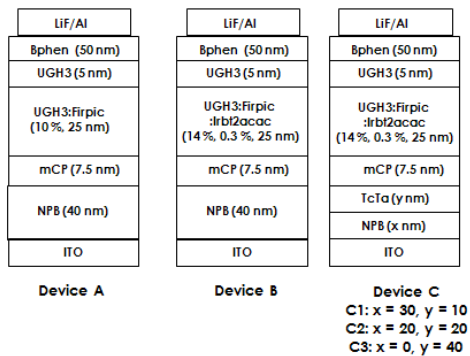


Fig. 1. Schematic diagrams of the structures of the blue and white PHOLEDs tested in this study.

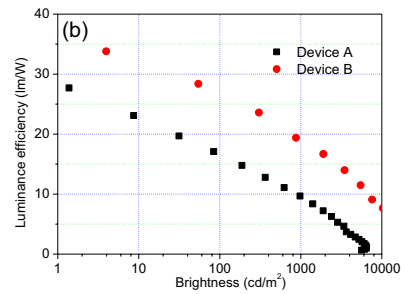
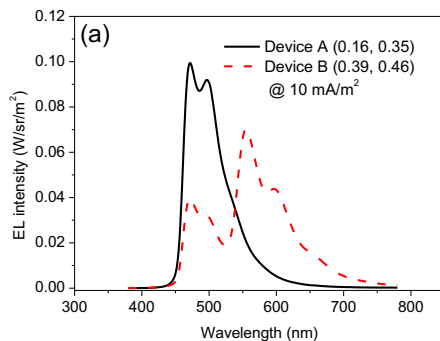


Fig. 2. Results for Device A and B : electroluminescence spectra; (b) power efficacy vs. brightness.

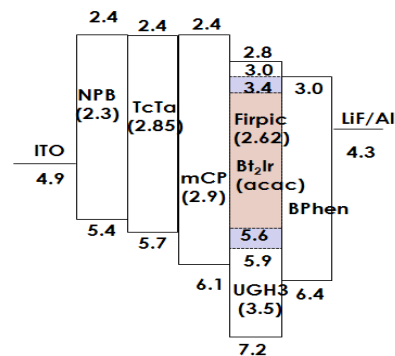


Fig. 3. Energy level diagrams for the materials used in this study.

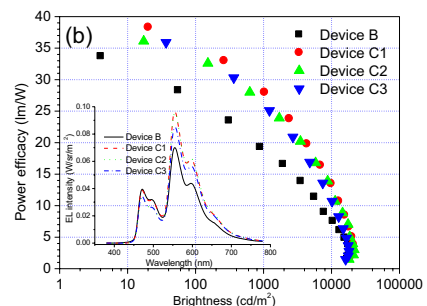
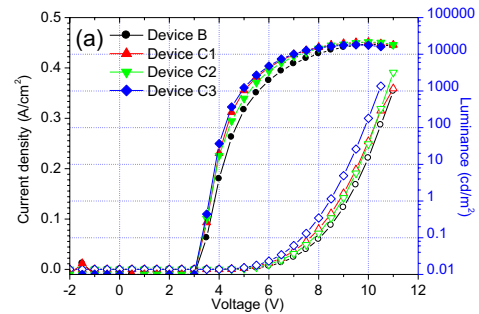


Fig. 4. Results for Device B and C : Current density vs. voltage (*I-V*) and voltage vs. luminance (*V-L*) characteristics; (b) power efficacy vs. brightness (Inset : electroluminescence spectra).

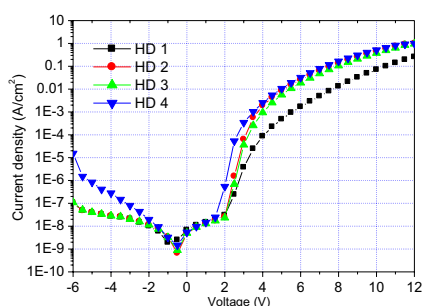


Fig. 5. I-V characteristics of hole only devices.

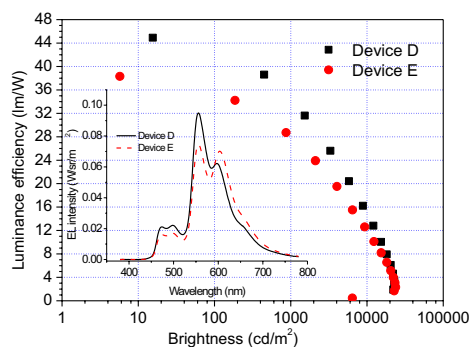


Fig. 6. Results for Device D and E : power efficacy vs. brightness (Inset : electroluminescence spectra).



Fig. 7. Photograph of White OLED in this study (100 x 100 mm²).

4. Summary

We have shown that improvement of WOLEDs efficiency could be obtained by engineering device architecture such as charge carrier injection/transporting layer and additional interlayer.

In addition, introducing a stepwise HTL system, we could obtain improved current density and reduced driving voltage, hence we reported highly efficient white OLEDs which has a power efficacies of 43.6 lm/W with CRI = 62 and 36 lm/W with CRI = 72 at 100 cd/m² without outcoupling enhancements. With outcoupling enhancements, the total power efficacy

increased to 74.1 lm/W and 61.2 lm/W.

5. Acknowledgements

This work was supported by the future technology development program of MOCIE/ITEP (2006-10028439, OLED lighting)

6. References

1. B. W. D'Andrade and S. R. Forrest. *Adv. Mater.* **16**, 1595 (2004).
2. R. Duggal, J. J. Shiang, C. M. Heller, D. F. Foust, *Appl. Phys. Lett.* **80**, 3470 (2002)
3. V. Adamovich, J. Brooks, A. Tamayo, A. M. Alexander, P. I. Djurovich, B. W. D'Andrade, C. Adachi, S. R. Forrest, and M. E. Thompson, *New J. Chem.*, **26**, 1171 (2002)
4. Y. -S. Park, J. -W. Kang, D. M. Kang, J. -W. Park, Y. -H. Kim, S. -K. Kwon, and J. -J. Kim, *Adv. Mater.* **20**, 1957 (2008)
5. R. J. Holmes, S. R. Forrest, Y. -J. Tung, R. C. Kwong, J. J. Brown, S. Garon, M. E. Thompson, *Appl. Phys Lett.* **82**, 2422 (2003).
6. M. A. Baldo, D. F. O'Brien, Y. You, Shoustikov, S. Sibley, M. E. Thompson, and S.R. Forrest, *Nature*, **395**, 151 (1998)
7. X. Ren, J. Li, R. J. Holmes, P. I. Djurovich, S. R. Forrest, and M. E. Thompson, *Chem. Mater.* **16**, 4743 (2004).
8. J. Lee, J. -I. Lee, K. -I. Song, S. J. Lee, and H. Y. Chu, *Appl. Phys. Lett.* **92**, 203305 (2008)
9. B. W. D'Andrade, J. -Y. Tsai, C. Lin, M. S. Weaver, P. B. Mackenzie, and J. J. Brown. *SID 07 Digest*. Vol. 38, p.1026 (2007).