# Highly efficient white organic light-emitting diodes using hybrid-spacer or/and codoped blue emitting layers

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**Keywords : white organic light-emitting diodes, hybrid-spacer, codoped blue emitting layers, the different functional material**

## Abstract

*The Authors have demonstrated highly efficient white organic light-emitting diodes using hybrid-spacer which was inserted between each emitting layer or/and codoped blue emitting layers with the different functional material. The characteristics of WOLEDs showed the maximum external quantum efficiency of 13.8%, power efficiency of 33.66 lm/W, and Commission Internationale de I'Eclairage coordinates of (x=0.36, y=0.37), respectively.*

## 1. Introduction

White organic light-emitting diodes (WOLEDs) have attracted increasing attention due to their potential use in a variety of applications such as the backlight of liquid crystal displays and full-color OLEDs and solid state lighting (SSL).[1]

One of the largest issues of WOLEDs as SSL is the low efficiency in comparison with fluorescent lamp. Thus, WOLEDs for high efficiency have been extensively studied by many research groups.[2] This letter reports a highly efficient WOLEDs using hybrid-spacer (HS) between each emitting layer (blue-red, red-green, and green-blue emissive layer), which was a fluorescent blue emitter, 4"-(2,2-diphenylvinyl)-1-[4-(N,N-diphenylamino)-styryl]-terphenyl (PVAS-tPh), phosphorescent green emitter, *fac*-tris(2-phenypyridine) iridium(III) ($Ir(ppy)_3$), and a red emitter, bis(5-benzoyl-2-phenylpyridinato-C,N)iridium(III) (acetylacetonate) ($(Bzppy)_2Ir(III)acac$) or/and codoped blue emitting layers (CBEML) with the different functional materials, N,N′-bis-(1-naphyl)-N,N′-diphenyl-1,1′-biphenyl-4,4′-diamine (NPB) and 4,7-diphenyl-1,10-phenanthroline (BPhen) which are used as charge transporting materials in OLEDs. The WOLEDs exhibited the maximum external quantum efficiency (EQE) of 13.8%, maximum power efficiency of 33.66 lm/W, and Commission Internationale de I'Eclairage ($CIE_{x,y}$) coordinates of (x=0.36, y=0.37), respectively.

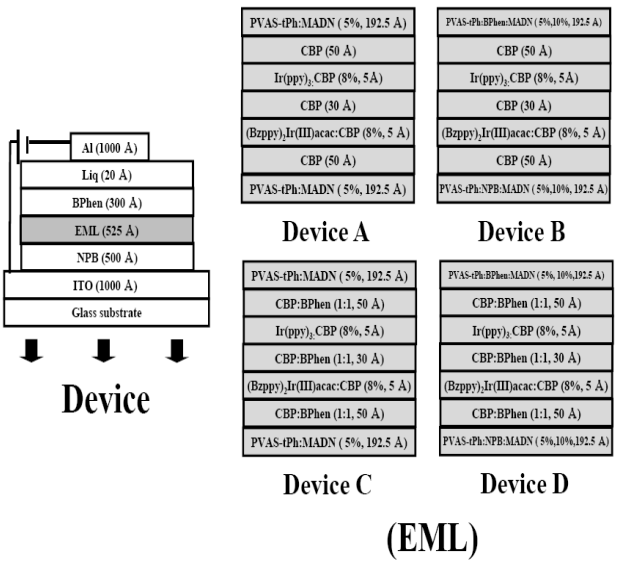


Fig. 1. The structures of all devices used in the experiment.

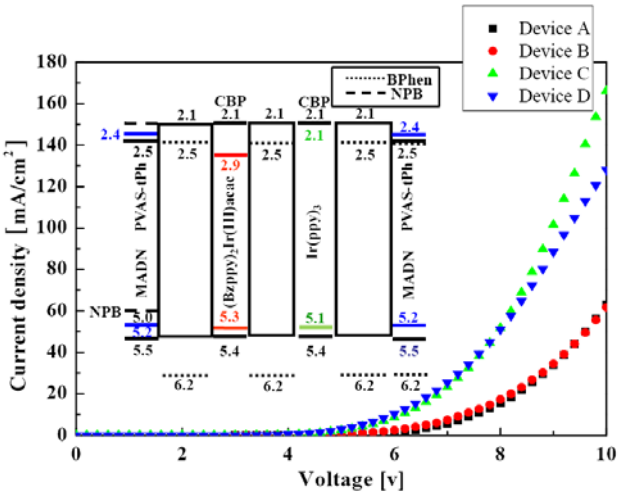


Fig. 2. Current density (J) *vs* voltages (V) characteristics of device A, B, C, and D.

## 2. Experimental

Indium tin oxide (ITO)-coated glass was cleaned in an ultrasonic bath by the following sequence: in acetone, methanol, distilled water and isopropyl alcohol. Thereafter, pre-cleaned ITO was treated by $O_2$ plasma with the conditions of 2 x $10^{-2}$ Torr, 125 W for 2 min. WOLEDs were fabricated using the high vacuum (5 x $10^{-7}$ Torr) thermal evaporation of organic materials onto the surface of the ITO-coated glass substrate (30 Ω/sq, emitting area was 3 mm x 3 mm). The deposition rates were 1.0 ~ 1.1 Å/sec for organic materials and 0.1 Å/sec for lithium quinolate (Liq), respectively. Without a vacuum break after the deposition of organic layers, the aluminum (Al) cathode was deposited at a rate of 10 Å/sec. The

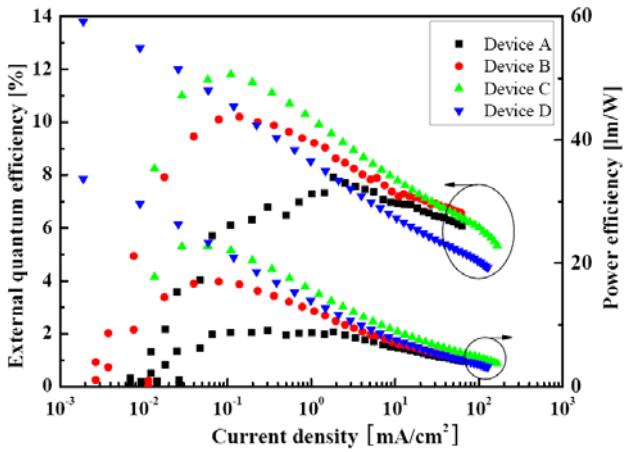


Fig. 3. The external quantum efficiency (EQE) and power efficiency (PE) *vs* current density (J) characteristics of device A, B, C, and D.

doping concentrations of the dopants were also optimized. With the DC voltage bias, the optical and electrical properties of WOLEDs such as the current density, luminance, luminous efficiency, power efficiency, and electroluminescence (EL) spectra of the emission characteristics were measured. The EQE and $CIE_{x,y}$ coordinates were calculated with Keithley 2400 and CHROMA METER CS-1000A instruments, respectively. All measurements were carried out under ambient conditions at room temperature.

## 3. Results and discussion

Figure 1 shows four devices fabricated with the following structure: ITO as the anode/NPB as the hole transporting layer (HTL)/PVAS-tPh doped in 2-methyl-9,10-di(2-naphthyl)anthracene (MADN) as the blue emitting layer (Device A and C) or PVAS-tPh and NPB doped in MADN (Device B and D) (BEML-1)/4,4'-bis(9-carbazolyl)-2,2'-biphenyl (CBP) spacer (CS) (device A and B) or hybrid CS:BPhen spacer (HCBS) (1:1) (device C and D) (CS-1)/$(Bzppy)_2Ir(III)acac$ doped in CBP as the red emitting layer (REML)/CS (device A and B) or HCBS (device C and D) (CS-2)/$Ir(ppy)_3$ doped in CBP as the green emitting layer (GEML)/CS (device A and B) or HCBS (device C and D) (CS-3)/ PVAS-tPh doped in MADN as the blue emitting layer (Device A and C) or PVAS-tPh and BPhen doped in MADN (Device B and D) (BEML-2)/BPhen as the electron transporting layer (ETL)/Liq electron injection layer (EIL)/Al as the cathode. The doping concentrations of PVAS-tPh and NPB in MADN, $(Bzppy)_2Ir(III)acac$ in CBP, and $Ir(ppy)_3$ doped in CBP were optimized to 5, 10, 8, and 8%, respectively.

It was shown in Fig. 2 that devices A, B, C, and D had a maximum current density of 63.12, 61.73, 166.09, and 128.03 mA/cm$^2$ at 10 V, respectively. Device C using HCBS showed the highest current density at the operating voltages among them because it seemed to be due to the smaller electron-injection barrier between the lowest unoccupied molecular orbital (LUMO) of BEML-2 and HCBS compared to it between the LUMO of BEML-2 and CS in inset Fig. 2. Therefore, device C and D using HCBS showed higher current density than device A and B with no HS. Device D had the lower current density than device C because NPB as codoped material showed better hole carriers mobility (HCM) and worse electron carriers mobility (ECM) and BPhen as codoped material showed better ECM and worse HCM than MADN

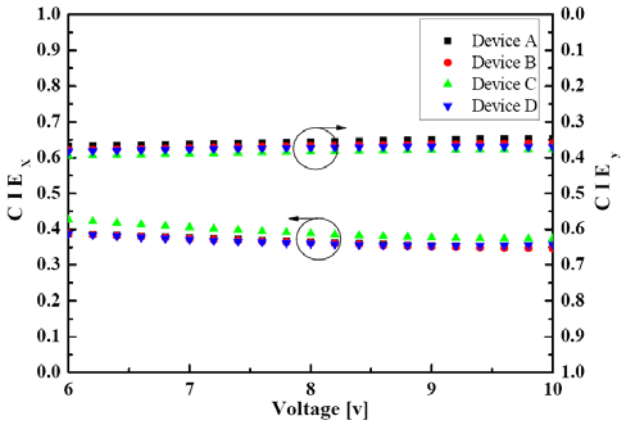


Fig. 4. Commission Internationale de l'Eclairage ($CIE_{x,y}$) coordinates from 6 V to 10 V of device A, B, C, and D.

without NPB and BPhen. Here, MADN as blue host material possesses a moderate hole and electron mobility of $10^{-7}$ $cm^2$ $V^{-1}$ $s^{-1}$.[3] NPB and BPhen used as codoped materials have a hole mobility of $10^{-4}$ $cm^2$ $V^{-1}$ $s^{-1}$ and an electron mobility of $10^{-4}$ $cm^2$ $V^{-1}$ $s^{-1}$.[4,5] respectively. Even though the electron mobility of NPB and hole mobility of BPhen were not found in the literature, it seemed to have poor transport properties.[5]

As shown in Fig. 3, devices A, B, C, and D had a maximum EQE of 7.92, 10.2, 11.8, and 13.8% at 1.837, 0.134, 0.110, and 0.002 mA/$cm^2$ and power efficiency of 9.09, 17.04, 22.75, and 33.66 lm/W at 0.301, 0.079, 0.058, and 0.002 mA/$cm^2$, respectively. They also showed theEQE of 7.28, 9.22, 9.91, and 8.52% and power efficiency of 7.43, 3.41, and 11.60% at 100 cd/$m^2$ and a power efficiency of 8.73, 12.20, 14.96, and 13.92 lm/W at 1 mA/$cm^2$, respectively. This suggests that the HCBS in device C effectively enhanced the recombination of holes and electrons and device B using CBEML effectively enhanced recombination probability of holes and electrons by blocking of hole and electron. Device B also enhanced efficiency by reduced quenching for expanded BEML preventing high exciton density because NPB codoped in BEML-1 had electron trap site as lower electron mobility and BPhen codoped in BEML-2 had hole trap site as lower hole mobility and higher HOMO level. Therefore, device D using CBEML and HCBS showed the highest EQE and power efficiency among them.

Figure 4 shows the $CIE_{x,y}$ coordinates versus operating voltages from 6 to 10 V of device A, B, C, and D. They had an emission of $CIE_{x,y}$ coordinates from (x=0.39, y=0.37), (x=0.39, y=0.38), (x=0.43, y=0.39), and (x=0.39, y=0.38) at 6 V to (x=0.35, y=0.35), (x=0.35, y=0.36), (x=0.37, y=0.38), and (x=0.36, y=0.37) at 10 V, respectively. Device D showed the smallest color shift with $\Delta CIE_{x,y}$ of $\pm$ (0.03, 0.01) from 6 to 10 V among them.

## 4. Summary

We demonstrated in this letter that WOLEDs using HS or/and CBEML with the different functional materials and blue fluorescent, red and green phosphorescent emitters were fabricated in order to improve the device efficiency. The white devices with the optimized structure showed the maximum external quantum efficiency of 13.8%, power efficiency of 33.66 lm/W, and $CIE_{x,y}$ coordinates of (x=0.36, y=0.37), respectively.

## 5. References

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