

Efficient white organic light-emitting diodes with a doped hole-blocking layer

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Abstract

We report very efficient white OLEDs consisting of a blue-emitting 4,4'-bis[N-(1-naphthyl)-N-phenyl-amino]-biphenyl (α -NPD), a hole-blocking layer of 2,9-dimethyl-4,7-diphenyl-1,10-phenanthroline (BCP) doped with red fluorescent dye of 4-dicyanomethylene-2-methyl-6-[2-(2,3,6,7-tetrahydro-1H,5H-benzo[i,j]quinolizin-8-yl)vinyl]-4H-pyran (DCM2), and green-emitting tris(8-hydroxyquinoline) aluminum (Alq_3). The device with the structure of ITO/ α -NPD (50 nm)/BCP:DCM2 (0.8 %, 4 nm)/ Alq_3 (50 nm)/LiF (0.5 nm)/Al shows a white emission with the CIE coordinates (0.329, 0.333). The maximum luminance of 20,800 cd/m^2 is obtained at 15.4 V. The power efficiency is 2.6 lm/W and the external quantum efficiency is 2.1 % at a luminance of 100 cd/m^2 at the bias voltage of 6 V.

1. Introduction

White organic light-emitting diodes (OLEDs) have attracted a lot of interests for their applications to a full-color display combined with color filters or the backlight in liquid crystal displays (LCDs) [1,2]. For these applications, it is very important to develop a high-brightness, high-efficiency, white light-emitting OLEDs. To obtain white emission from an OLED, two or more colors from different emitting molecules are combined. This can be done using a multilayer structure with two or more emitting layers [3-6]. Another method is either doping a polymer host with red, blue, and green fluorescent dyes or blending several light-emitting polymers [7,8]. Careful control of the location of exciton recombination zone and/or the energy transfer between the host and dopant molecules are needed to obtain a balanced white emission with Commission Internationale d'Eclairage (CIE) chromaticity coordinates of (0.33, 0.33).

In this work, we report the fabrication and the characterization of white light-emitting multilayer

OLEDs. The devices are fabricated using successive vacuum deposition of blue-emitting 4,4'-bis[N-(1-naphthyl)-N-phenyl-amino]-biphenyl (α -NPD) which also acts as a hole-transporting layer, a hole-blocking layer of 2,9-dimethyl-4,7-diphenyl-1,10-phenanthroline (BCP), doped with red fluorescent dye of 4-dicyanomethylene-2-methyl-6-[2-(2,3,6,7-tetrahydro-1H,5H-benzo[i,j]quinolizin-8-yl)vinyl]-4H-pyran (DCM2), and green-emitting tris(8-hydroxyquinoline) aluminum (Alq_3) which also acts as an electron-transporting layer. Fig. 1 shows the molecular structure of organic materials and the device structure. The BCP layer plays a dual role as a hole blocking layer and a host for DCM2 dopant. The thickness of BCP layer and the concentration of DCM2 are tuned to obtain a balanced white emission with Commission Internationale d'Eclairage (CIE) chromaticity coordinates of (0.33, 0.33).

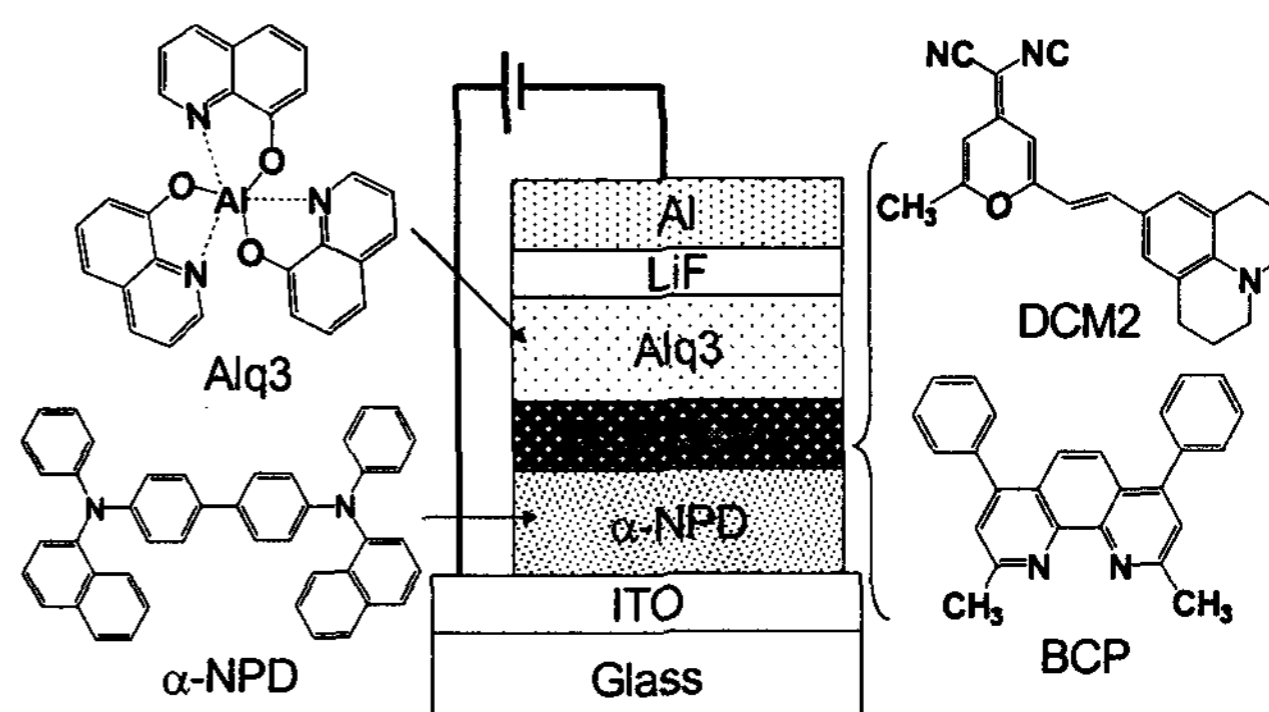


Figure 1 The molecular structure of organic materials and the device structure of ITO/ α -NPD (500 Å)/BCP:DCM2 (10 ~ 60 Å)/ Alq_3 (500 Å)/LiF (5 Å)/Al.

2. Experimental

The devices are fabricated by using successive vacuum-depositions of α -NPD (500 Å), BCP doped with DCM2 (10~60 Å), and Alq_3 (500 Å), LiF (5 Å),

and Al electrode, without breaking vacuum, onto etched and cleaned indium tin oxide (ITO) substrates. The ITO substrates with a sheet resistance of about $10 \Omega/\square$ are supplied by Samsung Corning Inc. The overlap area of the Al and ITO electrodes is about 4 mm^2 . The sublimed α -NPD, Alq_3 , and DCM2 purchased from SynTec, and BCP purchased from Aldrich were used as received. The evaporation rates are about $2 \text{ \AA}/\text{s}$, measured by a quartz crystal oscillator, under a base pressure of about 1×10^{-6} Torr. The doping concentration of DCM2 in BCP is controlled by monitoring the evaporation rate of each material.

The device performance was studied by measuring the current-voltage-light (I-V-L) characteristics, electroluminescence (EL) spectra at room temperature under vacuum. The I-V characteristics were measured with a Keithley 236 source-measure unit. The intensity of the EL emission from the devices was simultaneously measured with a Keithley 2000 multimeter equipped with a calibrated Si photodiode or a PMT through an ARC 275 monochromator.

3. Results and discussion

Fig. 2 shows the EL spectra for devices with different thicknesses of the BCP:DCM2 layer with the doping concentration of 0.8 % under the current density of $17 \text{ mA}/\text{cm}^2$. The inset shows the ratio of DCM2 to α -NPD peak intensities as a function of the BCP:DCM2 thickness. The EL spectra consist of two strong peaks around 460 nm (α -NPD) and 580 nm (DCM2) and a peak around 510 nm (Alq_3). As the thickness of the BCP:DCM2 layer increases, the emission from α -NPD increases significantly due to the hole-blocking property of BCP.

The ratio of DCM2 to α -NPD emission and the Alq_3 emission increases with decreasing the BCP:DCM2 layer thickness, indicating the increase in the probability of the hole transport through the BCP:DCM2 layer as well as the Förster energy transfer from α -NPD to Alq_3 and to DCM2. Deshpande *et al.* [6] observed similar phenomena in the device of ITO/ α -NPD:DCM2/BCP/ Alq_3 /MgAg, and they explained the process as the interlayer sequential energy transfer where the excitation energy is transferred sequentially from α -NPD to Alq_3 and to DCM2, twice across the thin BCP layer [6].

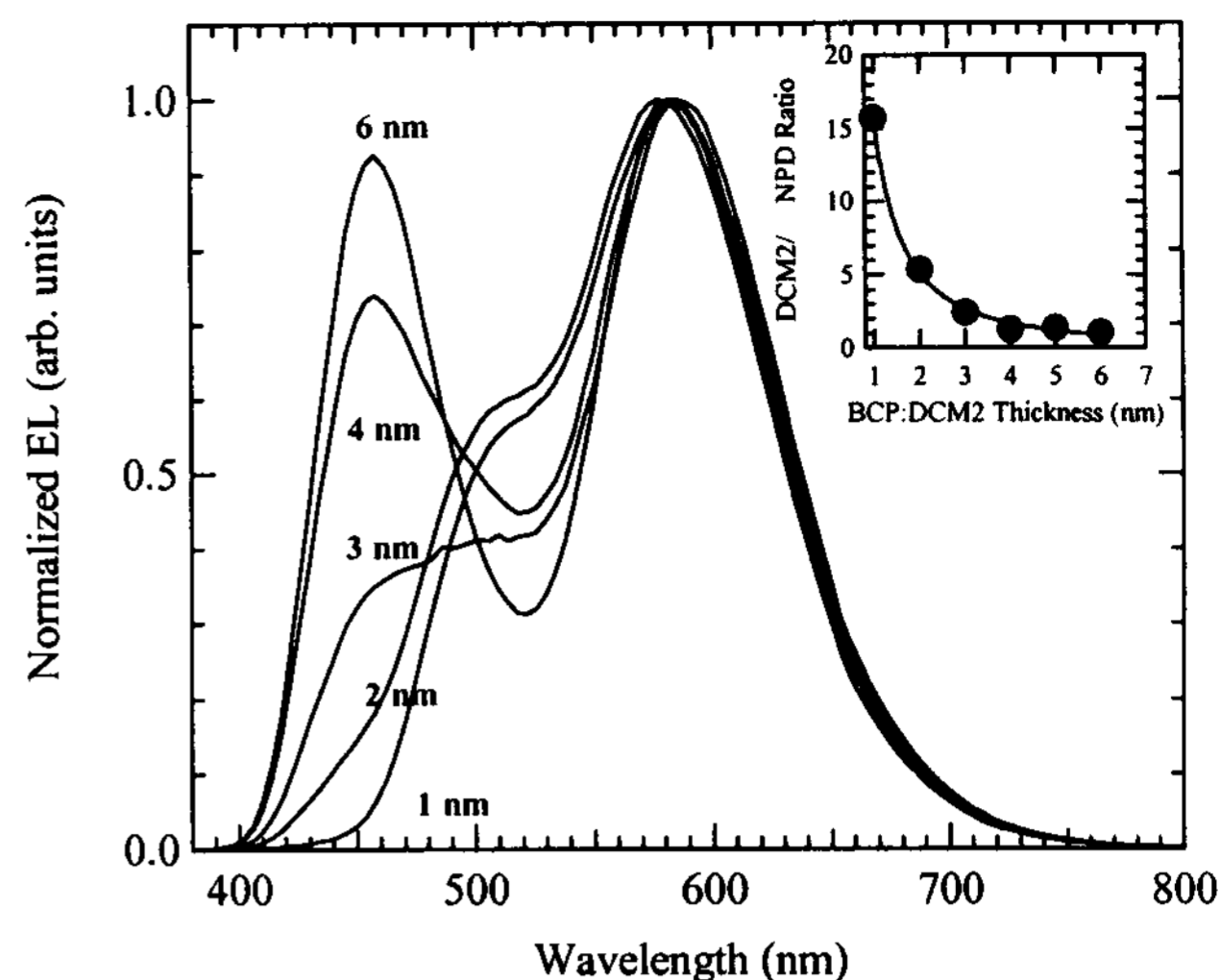


Figure 2 The EL spectra for devices with different thicknesses of the BCP:DCM2 layer with the doping concentration of 0.8 % under the current density of $17 \text{ mA}/\text{cm}^2$. The inset shows the ratio of DCM2 to α -NPD peak intensities as a function of the BCP:DCM2 thickness.

We can obtain white light-emission by adjusting the thickness of the BCP:DCM2 layer which controls the relative intensities of blue (α -NPD) and red (DCM2) EL emission peaks. White light-emission is obtained for the devices with the thickness of the BCP:DCM2 layer in the range between 40 and 60 \AA . Fig. 3 shows the variation of EL spectra with the current density for the device of ITO/ α -NPD (500 \AA)/BCP:DCM2 (0.8 %, 40 \AA)/ Alq_3 (500 \AA)/LiF (5 \AA)/Al. The inset shows the CIE chromaticity diagram with the coordinates of the corresponding spectra. As the current density increases, the blue part of the EL spectra increases slightly relative to the red part, resulting in a slight shift of the CIE coordinates from (0.385, 0.364) at current density of $18 \text{ mA}/\text{cm}^2$ to (0.313, 0.322) at $140 \text{ mA}/\text{cm}^2$. This indicates that the distribution of hole concentration across the hole-blocking layer of BCP changes with the current density (bias voltage), and thereby changing the distribution of excitons over the α -NPD and BCP:DCM2 layers. At the current density $100 \text{ mA}/\text{cm}^2$, the device shows the balanced white light-emission with the CIE coordinates of (0.329, 0.333).

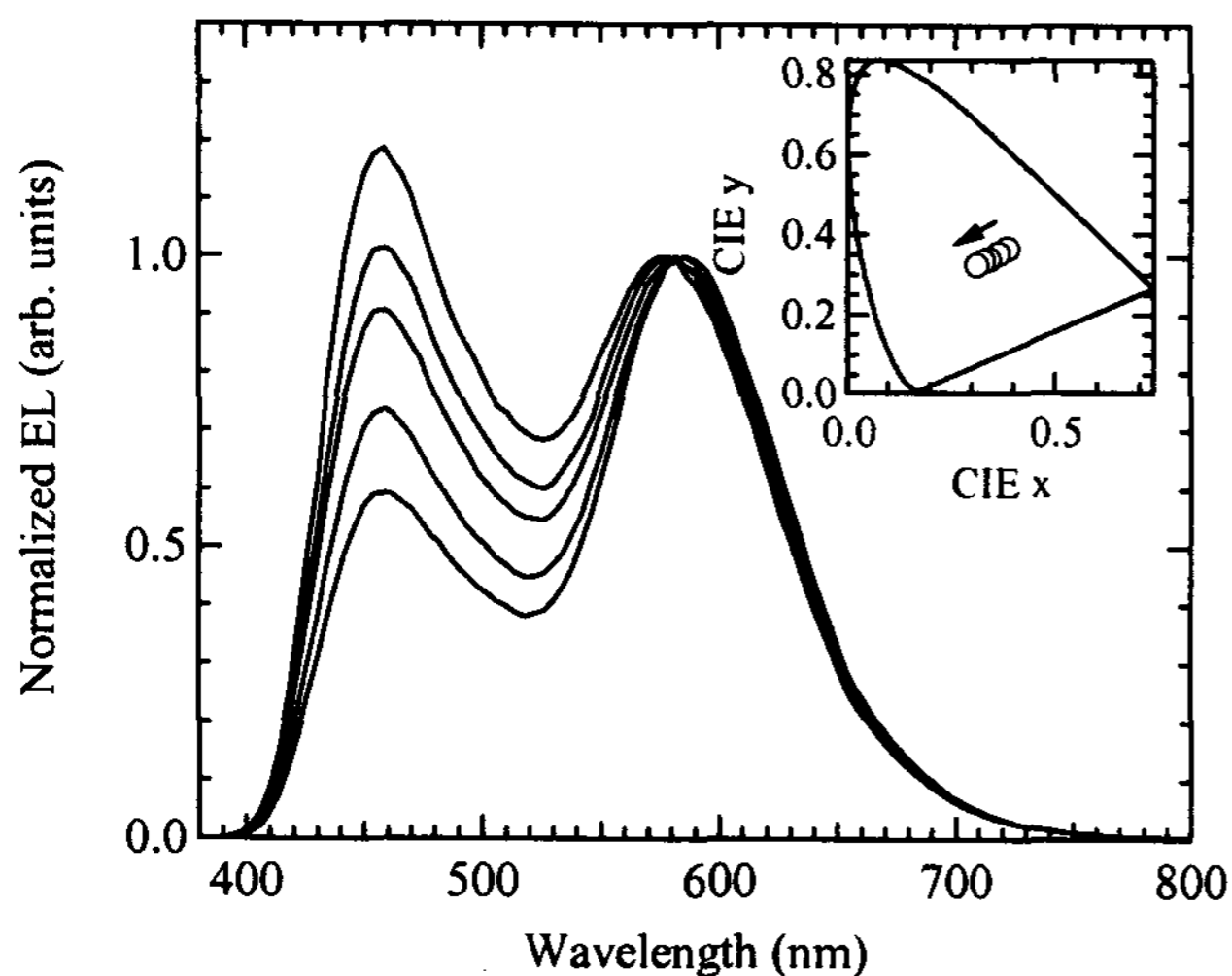


Figure 3 Variation of EL spectra with the current density for the device of ITO/ α -NPD (500 Å)/BCP:DCM2 (0.8 %, 40 Å)/Alq₃ (500 Å)/LiF (5 Å)/Al, along with the CIE chromaticity coordinates in the inset. The current densities for the curves are 18, 35, 70, 100, and 140 mA/cm² (from bottom to top).

Fig. 4 shows the current-voltage-luminescence (I-V-L) characteristics of ITO/ α -NPD (500 Å)/BCP:DCM2 (0.8 %, 40 Å)/Alq₃ (500 Å)/LiF (5 Å)/Al. The inset shows the external quantum efficiency (QE) and the luminous efficiency as the function of the current density for the same device. The I-V-L characteristics exhibit a power-law dependence, indicating the trap-limited current [9]. The onset voltage of the light emission is about 2.6 V. The device shows an external QE of about 2.1 % and a luminous efficiency of 2.6 lm/W at luminance 100 cd/m² (bias voltage 6 V and current density 2 mA/cm²). The maximum luminance of about 20,800 cd/m² was achieved at 15.4 V and 1370 mA/cm².

4. Conclusion

We have reported efficient white OLEDs consisting of blue-emitting α -NPD and a red emitting BCP:DCM2. The spectral emission depends on both the DCM2 concentration in the BCP hole blocking layer and its thickness. By tuning the thickness of BCP layer and the concentration of DCM2 we obtained a balanced white emission with the CIE coordinates of (0.33, 0.33). The device shows an

external QE of about 2.1 % and a luminous efficiency of 2.6 lm/W at luminance 100 cd/m² (bias voltage 6 V and current density 2 mA/cm²). The maximum luminance of about 20,800 cd/m² was achieved at 15.4 V and 1370 mA/cm².

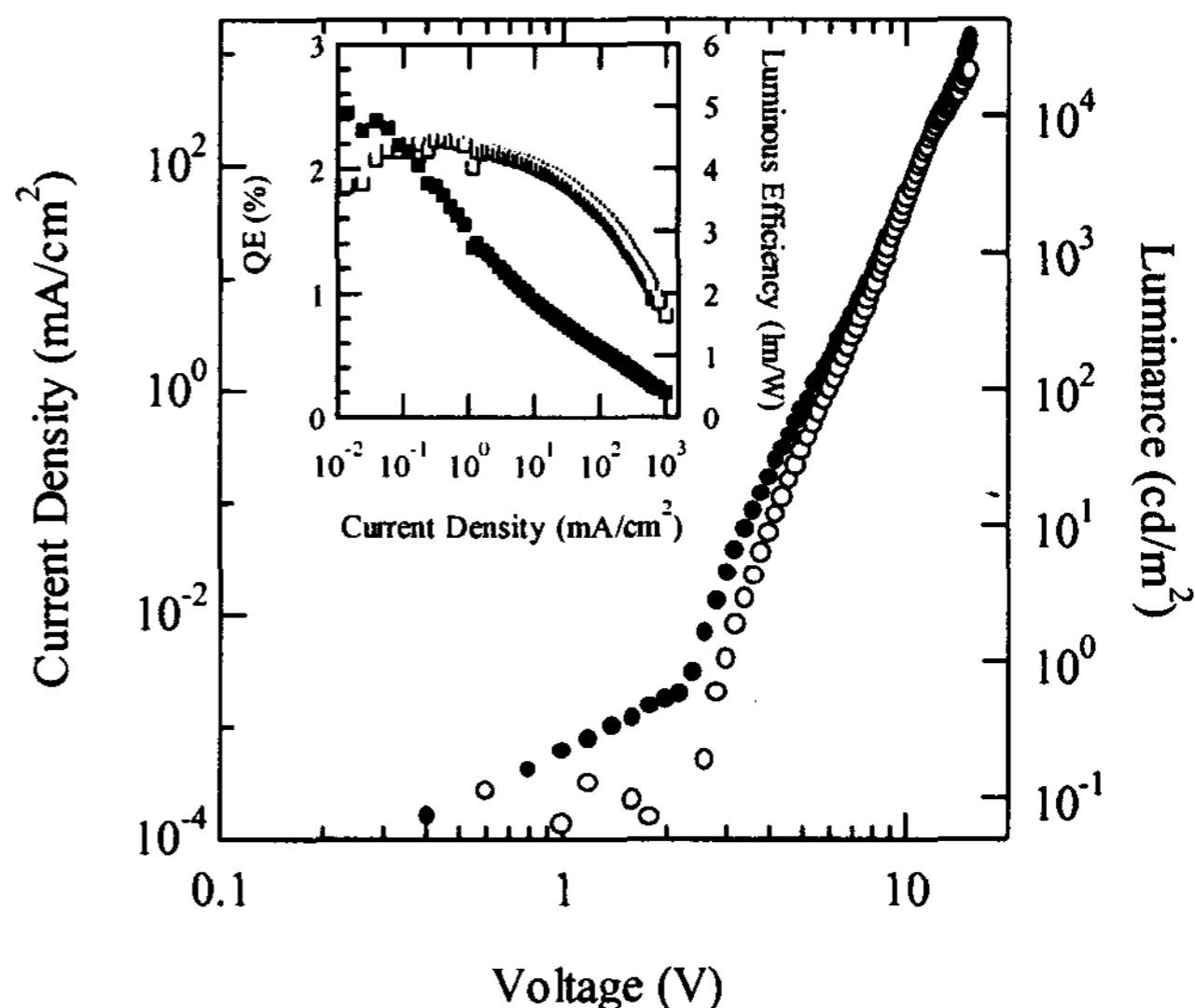


Figure 4 The current-voltage-luminescence characteristics of ITO/ α -NPD (500 Å)/BCP:DCM2 (0.8 %, 40 Å)/Alq₃ (500 Å)/LiF (5 Å)/Al. The inset shows an external quantum efficiency (QE) and the power efficiency as a function of the current density for the same device.

5. Acknowledgements

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6. References

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