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Device characteristics of alternating-current-driven colour-tunable phosphorescent organic light-emitting diodes

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Abstract. We demonstrate alternating-current (AC)-driven colour-tunable organic light-emitting diodes (OLEDs) with vertically stacked green and red phosphorescent OLED units. Optically optimized thicknesses of hole and electron transporting layers were investigated through optical simulation. In addition, two types of red host materials were used for the red OLED unit, and the red OLED unit with 4,4′-Bis(N-carbazolyl)-1,1′-biphenyl showed higher current efficiency compared to that of the red OLED unit with 2,6-Bis(3-(9H-carbazol-9-yl)phenyl)pyridine. The fabricated colour-tunable exhibited red and green colours when the duty ratio was 1% and 99%, respectively. Furthermore, the device can produce various colours that are a mixture of green and red by adjusting the AC-driving duty ratios.

1 Introduction

Organic light-emitting diodes (OLEDs) have received great attention as next generation displays owing to their fast response time, high contrast ratio, thinness, light weight, low power consumption, and flexibility. Red (R), green (G), and blue (B) sub-pixels are necessary for implementing full-color displays. Fine metal mask (FMM), white OLED (WOLED) with colour filters, and inkjet printing methods are generally utilized for patterning R, G, B sub-pixels. The FMM method is employed for small size OLED displays such as mobile and tablet devices. However, it has some problems such as thermal expansion, susceptible to mechanical bending, and challenging to handle when scaled up in size, making it impractical for large-area and high-resolution display applications [1]. The WOLED with colour filters method is used for large size OLED displays such as TVs, but low luminance and efficiency are critical problems in this method. Inkjet printing method is still not used for practical products due to low operating lifetime of solution process-based OLEDs compared with that of thermal evaporation process-based OLEDs.

Colour-tunable OLEDs can realize various colours in the same pixel without R, G, B sub-pixels patterning. They typically consist of colour units and semi-transparent intermediate electrodes. There are two types of colour-tunable OLEDs which are direct-current (DC) and alternating-current (AC)-driven devices [2–4]. DC-driven devices with two colour units typically require three or four driving lines for controlling driving voltages, whereas AC-driven devices with two colour units need only two driving lines by adjusting duty ratios.

In this study, AC-driven colour-tunable phosphorescent OLEDs were fabricated with green and red colour units. Hole and electron transporting layers were optimized through optical simulation. Two types of host materials which were 4,4′-Bis(N-carbazolyl)-1,1′-biphenyl (CBP) and 2,6-Bis(3-(9H-carbazol-9-yl)phenyl)pyridine (26DCzPPy), were used in the red emitting layer (EML). The red colour unit exhibited different current efficiency depending on host materials. The fabricated colour-tunable OLEDs showed different colour coordinates and colours depending on AC-driving duty ratios.

2 Results and discussion

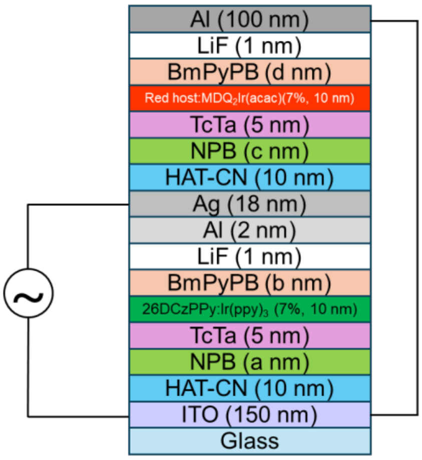

Fig. 1. Schematic device structure of AC-driven colour-tunable phosphorescent OLEDs.

Figure 1 shows AC-driven colour-tunable OLEDs with red and green phosphorescent OLED units. Indium tin oxide (ITO) was utilized as an anode. 1,4,5,8,9,11-hexaazatriphenylenehexacarbonitrile (HAT-CN) and N,N′-diphenyl-N,N′-bis(1-naphthyl)-1,1′-biphenyl-4,4″-diamine (NPB) served as a hole injection layer and hole

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transporting layer (HTL), respectively. 4,4′,4″-tri(N-carbazolyl)triphenylamine (TcTa) and 1,3-bis(3,5-dipyrid-3-yl-phenyl)benzene (BmPyPB) were used as an exciton blocking layer and electron transporting layer (ETL), respectively. Fac-tris(2-phenylpyridine)iridium(III) ($Ir(ppy)_3$) and bis(2-methyldibenzo[f,h]-quinoxaline)(acetylacetonate)iridium(III) $(MDQ)_2Ir(acac)$ were employed as green and red phosphorescent dopants, respectively. Lithium fluoride (LiF) and Al, Ag were used as an electron injection layer and metal electrodes, respectively.

The total thickness of green and red OLED units is a significant factor in determining the luminance, efficiency, and electroluminescence spectra of the devices due to the microcavity effect caused by intermediate and top meal electrodes [5]. The thicknesses of the HTLs and ETLs of the green and red OLED units were changed in the optical simulation. For high current efficiency of the red OLED unit, the thicknesses of a, b, c, and d were 50 nm, 20 nm, 50 nm, and 60 nm, respectively, regardless of the red host materials. On the other hand, the thicknesses of a, b, c, and d for high current efficiency in the green OLED unit were 100 nm, 60 nm, 60 nm, 70 nm, and 100 nm, 60 nm, 50 nm, 80 nm in devices with 26DCzPPy and CBP host materials, respectively. Although these thicknesses are optically meaningful, thick thicknesses of HTL and ETL can increase the driving voltage of the device. Therefore, the thickness of a, b, c, and d were fixed at 30 nm in the fabricated device by considering electrical and optical properties.

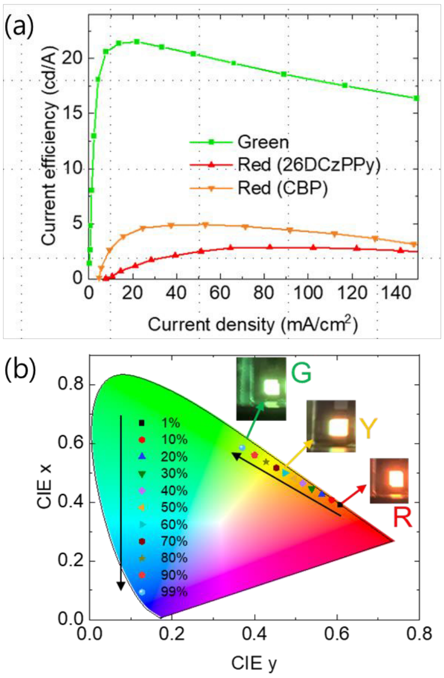

Fig. 2. (a) Current efficiency of the red and green OLED units with different red host materials, (b) change of CIE 1931 colour coordinates of the colour-tunable OLEDs depending on AC-driving duty ratios

Figure 2(a) exhibits the current efficiency of the red and green OLED units with different red host materials. The efficiency of the green OLED unit remains nearly the same regardless of the red host materials, with its maximum current efficiency was 21.52 cd/A at 21.96 mA/cm^2. The red OLED unit with CBP shows higher current efficiency compared to that of the red OLED unit with 26DCzPPy due to the higher charge carrier mobility of CBP compared to 26DCzPPy. The red OLED unit shows lower current efficiency compared to the green OLED unit. The low optical transmittance of the Al (2 nm)/Ag (18 nm) intermediate electrode can be one of reasons for this low efficiency.

Figure 2(b) depicts Commission Internationale de l'Éclairage (CIE) 1931 colour coordinates of the colour-tunable OLEDs with different AC-driving the duty ratios. The device exhibits different colours depending on duty ratios. For instance, the device shows red colour with CIE colour coordinates of (0.608, 0.390) when the duty ratio was 1%. Conversely, when the duty ratio is 99%, the device exhibits green colours with CIE colour coordinates of (0.370, 0.585). By adjusting the duty ratios, the device can produce various colours that are a mixture of green and red. For example, when the duty ratio is 70%, the device shows yellow colours with CIE colour coordinates of (0.453, 0.516).

3 Conclusion

AC-driven colour tunable-OLEDs were successfully fabricated using red and green phosphorescent OLED units. The red OLED unit with CBP host shows higher current efficiency compared to that of the red OLED unit with 26DCzPPy host. On the other hand, the efficiency of the green OLED unit emains the same regardless of the red EML host materials. The colour-tunable OLEDs implement various colours which are mixed with green and red colours by changing AC-driving duty ratios. Therefore, this colour tunable-OLEDs can be helpful to reduce sub-pixel patterning process.

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