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High-efficiency low color temperature organic light emitting diodes with solution-processed emissive layer

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ABSTRACT

Low color temperature (CT) lighting provides a warm and comfortable atmosphere and shows mild effect on melatonin suppression. A high-efficiency low CT organic light emitting diode can be easily fabricated by spin coating a single white emission layer. The resultant white device shows an external quantum efficiency (EQE) of 22.8% (34.9 lm/W) with CT 2860 K at 100 cd/m^2, while is shown 18.8% (24.5 lm/W) at 1000 cd/m^2. The high efficiency may be attributed to the use of electroluminescence efficient materials and the ambipolar-transport host. Besides, proper device architecture design enables excitons to form on the host and allows effective energy transfer from host to guest or from high triplet guest to low counterparts. By decreasing the doping concentration of blue dye in the white emission layer, the device exhibited an orange emission with a CT of 2280 K. An EQE improvement was observed for the device, whose EQE was 27.4% (38.8 lm/W) at 100 cd/m^2 and 20.4% (24.6 lm/W) at 1000 cd/m^2.

1. Introduction

Color temperature (CT) of a lighting source plays an important role in human physiology and psychology [1–7]. Lighting with low CT, which was generally defined below 5500 K corresponding to CT of pure-white lighting above 5500 K, provides a warm and comfortable atmosphere and helps stabilize autonomic nervous function [8]. Most importantly, it shows a milder suppression effect on the secretion of melatonin (MLT) [9,10]. Being constantly exposed to the light with high color temperature, however, will stimulate the secretion of cortisol that makes people awake and more active [1,3,7] but will markedly suppress the nocturnal secretion of MLT, increasing the risk of being afflicted with cancers, such as breast, colorectal, prostate etc. [4]. Therefore, a proper lighting source with suitable color temperature will be an important issue which most people are unaware of.

In typical lighting options, low CT devices include candles, incandescent bulbs, and warm-white fluorescent lamps. However, the first two aforementioned lighting devices are energy wasting. For example, the respective power efficiency is 0.1 and 15 lm/W. In solid-state lighting, organic light emitting diodes (OLEDs) provide a new alternative, which is energy saving and CT tailorable [11,12]. For example, Leo et al. reported a power efficiency of 38 lm/W with 3180 K at 100 cd/m^2 [13], So et al. mentioned a power efficiency of 40 lm/W with 4970 K [14], and Kido et al. published a finding of 55 lm/W with 5340 K [15]. All these were fabricated via vapor deposition. For solution-processed devices, Tokito et al. reported 16.2 lm/W with 4270 K at 100 cd/m^2 [16], Forrest et al. found a result of 12.2 lm/W with 4750 K [17], and Yang et al. reported a power efficiency of 16 lm/W with 4660 K [18]. Although solution process provides numerous

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advantages, such as high throughput, large-area size and low cost [19], the efficiency of wet-processed devices was apparently lower than that of the vapor deposition processed counterparts. Also, the aforementioned devices have high efficiencies yet their CTs are relatively higher. Therefore, the efficiency of wet-processed OLEDs with low CT needs further improvement. Numerous approaches have been reported to obtain high efficiency, such as electroluminescence (EL) efficient materials, and structure with low carrier injection barrier, effective carrier or exciton confinement, excitons forming on the host, balanced carrier injection, and efficient host-to-guest energy transfer [11,20–29].

This study demonstrates two high-efficiency low CT OLEDs with a solution-processed hole-injection layer (HIL) and an emissive layer (EML). One device showed a power efficiency of 34.9 lm/W (55.9 cd/A) at 100 cd/m^2 or 24.5 lm/W (46.0 cd/A) at 1000 cd/m^2 with white emission of CT ranging between 2860 and 3030 K, while the power efficiency of the other one was 38.8 lm/W (55.9 cd/A) at 100 cd/m^2 or 24.6 lm/W (46.0 cd/A) at 1000 cd/m^2 with orange emission of CT ranging between 2280 and 2320 K.

The high-efficiency low CT white device is comprised of an anode layer of indium tin oxide, a HIL of PEDOT:PSS, an EML containing 0.6 wt.% tris(2-phenylquinoline)iridium(III) [Ir-(2-phq)$_3$] (orange-red dye), 0.2 wt.% bis[5-methyl-7-trifluoromethyl-5*H*-benzo(*c*)(1,5)naphthyridin-6-one]iridium(picolinate) (CF$_3$BNO, green dye), and 14 wt.% bis(3,5-difluoro-2-(2-pyridyl)-phenyl-(2-carboxypyridyl)iridium(III) (FIrpic, blue dye), doped in a 4,4′-bis(carbazol-9-yl)biphenyl (CBP) host, an electron transporting layer (ETL) of 1,3,5-tris(*N*-phenylbenzimidazol-2-yl)benzene (TPBi), an electron injection layer (EIL) of lithium fluoride (LiF) and a cathode layer of aluminum (Al). 3,5-Di(9H-carbazol-9-yl)tetraphenylsilane (SimCP2) and 4,4′,4″-tri(N-carbazolyl)triphenylamine (TCTA) hosts were also used in device fabrication.

Fig. 1 compares the power efficiency of devices devised for this work and other previously reported solution-processed white OLEDs with respect to CT. The best reported power efficiency of solution-processed white OLEDs was 25 lm/W (39 cd/A) [30]. However, its emission is cold-white, i.e. beyond CT 6500 K. On the other hand, for lower CT emissions, such as pure- and warm-white light from 2500 to 6500 K, the best reported efficiency also shown in Fig. 1 was 16.2 lm/W [16]. This study demonstrated a high-efficiency warm-white OLED (marked with II) with a power efficiency of 34.9 lm/W (55.9 cd/A) and CT of 2860 K. In addition to a white device, an orange OLED (marked with VII) with a higher relative power efficiency of 38.8 lm/W (66.5 cd/A) and a lower CT of 2280 K was presented. Its EL spectrum is shown in the inset.

The ambipolar-transport property of the host plays an important role in the resultant current efficiency. Fig. 2 shows the current efficiency of the devices using three different hosts with the same doping concentrations. At all current densities, the CBP-composed device showed the highest efficiency of all. For example, at low current densities, such as 0.1 mA/cm^2 used for displays applications, the CBP-composed device showed an efficiency of 55.9, 32 cd/A for SimCP2, and only 30 cd/A for TCTA. Moreover, at high current densities, such as 10 mA/cm^2 used for illumination applications, the efficiency of the CBP-composed counterpart was 37.4, 26.8 cd/A for SimCP2, and 21.5 cd/A for TCTA. Since CBP and SimCP2 are ambipolar hosts, the better balance between hole and electron injection in the device may explain the better current efficiency of the device. On the other hand, TCTA is a hole-transporting host, which allows more holes to be injected into the EML. This results in a less balanced carrier injection and, in turn, a lower efficiency.

Besides the ambipolar-transporting property, device architecture also plays an important role in the resultant device efficiency. Fig. 3 shows the energy-level diagram of the white devices using three different hosts. To obtain high efficiency, exciton formation on the host is known to be beneficial. For the SimCP2 host with the highest lowest unoccupied molecular orbital (LUMO) of 2.5 eV among the hosts, electrons from the TPBi ETL are favored to hop onto guests with lower LUMO. Besides, the highest occupied molecular orbital (HOMO) of the SimCP2 is 6.1 eV,

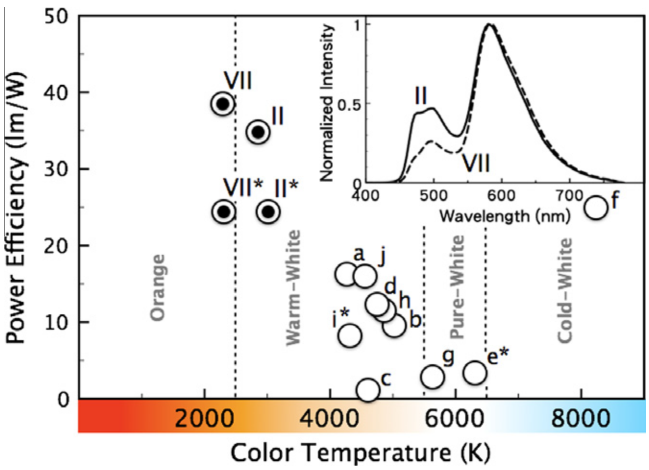

Fig. 1. Power efficiency at 100 cd/m^2 vs. color temperature of the studied devices herein (◉), compared with that of the reported counterparts via solution-process (○). The ones marked with star (*) show their respective efficiencies at 1000 cd/m^2. Inset shows the EL spectra of our studied OLEDs at 100 cd/m^2 [42].