Ultra-thin White Organic Light Emitting Diodes on Silicon (OLEDoS) for Low Driving Voltage with High Color Stability

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Keywords: micro-display, OLEDoS, virtual reality, augmented reality

ABSTRACT

Herein, we report white organic light emitting diodes on silicon (OLEDoS) devices with ultra-thin charge generation units (CGUs) of 10 nm thickness for augmented reality (AR) and virtual reality (VR) applications. In device performance, it showed low driving voltage of 6.2 V at 2,000 cd/m^2 and maximum luminance of 50,015 cd/m^2 at 10.0 V. Maximum current efficiency of 20.0 cd/A was achieved. It also showed high color stability of (0.155±0.001, 0.492±0.007) from 500 cd/m^2 to 2,000 cd/m^2 in Commission Internationale de l'Eclairage (CIE) 1976 color space.

1 INTRODUCTION

Recently, virtual reality (VR) and augmented reality (AR) devices for information display are in the spotlight as a next-generation display market. In VR and AR applications, micro-display is the one of the essential components to realize the vivid images. Currently, liquid crystal on silicon (LCoS) and organic light emitting diodes on silicon (OLEDoS) have been widely studied as representative micro-display technologies [1-3]. Especially, OLEDoS is an attractive technology due to its self-emitted characteristics, high contrast ratio, fast response time and high color purity.

There are two architectures of OLEDoS display; (1) the one is direct patterning type which is independently consisted red, green and blue emissive layers (EMLs) in each sub-pixel, (2) the other one is white OLEDoS with color filter. To achieve fine-size pixels for high resolution, the former is disadvantageous owing to the limitation of the fine-metal mask, hence, the latter is more suitable technology in micro-display field [4-5].

Meanwhile, tandem is the most common structure as white OLEDoS because of its color stability and tunability. But, the driving voltage of the complementary metal-oxide semiconductor (CMOS) backplane is restricted due to the fine-sized CMOS circuit corresponding to the pixel size [2]. It is the obstacle to obtaining high luminance in a tandem structure. In particular, it is a critical issue in achieving outdoor visibility in AR applications. Hence, improvement of driving voltage is one of the most crucial part in white OLEDoS device.

We developed white OLEDoS devices with the low driving voltage of 6.2 V at 2,000 cd/m^2 and high luminance of 50,015 cd/m^2 at 10.0 V. In addition, it also presented high color stability of (0.157±0.003, 0.495±0.008) according to the luminance variation from 500 cd/m^2 to 2,000 cd/m^2, which is comparable to previously reported [2].

2 EXPERIMENT

In this research, semiconducting emissive thin film optics simulator (SETFOS) was utilized to design tandem white OLEDoS device structures with proper device performances. In OLEDoS device fabrications, silicon wafer of CMOS backplane with aluminum / titanium nitride reflection anode by commercial foundry company were utilized. In white OLEDoS devices, 1,4,5,8,9,11-hexaazatriphenylene hexacarbonitrile (HATCN) was adopt as hole injection material. The commercial materials of hole transport layers (HTLs), blue fluorescent and yellowish-green (YG) phosphorescent EMLs, and electron transporting layer (ETL) were applied, respectively. To prohibit the exciton transporting into HTL, tris(4-carbazoyl-9-ylphenyl)amine (TCTA) was inserted between HTL and EML as an exciton blocking layers (EBLs). Ytterbium (Yb) and silver (Ag) were used as electron injection layer and semitransparent cathode, respectively. Commercial material of capping layer (CPL) was deposited on the cathode. Each organic and metal layer was thermally deposited in evaporation-based film pattern alignment system under 10^{-7} torr. The fabricated devices were encapsulated by glass can with ultraviolet curable resin in the nitrogen circumstances. The device performances of current density-voltage-luminance, efficacies and electroluminescence (EL) spectra were estimated by spectroradiometer (Konica Minolta CS-2000A) with Keithley 2400 source meter unit.

3 RESULTS

Prior to fabricate the devices, optical simulation was carried out to boost the device efficiency with appropriate emission color characteristics. As portrayed in Fig.1(a) and 1(b), 1st and 2nd antinode fields of the radiance were observed in accordance with the change of the distance from each electrode to EML. In order to achieve the high luminance efficiency with proper color property, based on the calculation results, we designed white tandem OLEDoS structures as follows;

Device W1: HATCN (10 nm) / HTL (35 nm) / EBL (10 nm) / YG EML (10 nm) / ETL (25 nm) / CGU (30 nm) / HTL (25 nm) / YG EML (10nm) / ETL (25nm) / Yb (1nm) / Ag (17nm) / CPL (60nm).

Device W2: HATCN (10 nm) / HTL (15 nm) / EBL (10 nm) / Blue EML (10 nm) / ETL (5 nm) / CGU (10nm) / HTL (5 nm) / YG EML (10nm) / ETL (25nm) / Yb (1nm) / Ag (17nm) / CPL (60nm).

Where, the device W1 is an ordinary white tandem structure based on simulation results and the device W2 is a newly attempted white tandem structure in which the ultra-thin CGU is applied.

From the designed device structures above, we fabricated OLEDoS devices. As depicted in Fig.2(a), the driving voltage of device W1 was 9.9 V at 2,000 cd/m^2 whereas device W2 presented significant driving voltage improvement as 6.2 V although the emission color characteristics of both devices were almost identical each other as showed in Fig.2(c). Moreover, device W2 showed maximum luminance of 50,015 cd/m^2 at 10.0 V on the other hand luminance of device W1 was 2,143 cd/m2 at the same driving voltage, in other words, it is almost 20 times higher luminance. Therefore, it implies that our device is more advantageous to ensure high outdoor visibility in AR applications.

Actually, the conventional white tandem device (device W2) showed slightly superior performance compared to our device in terms of power efficiency at low luminance region as depicted in Fig.2(b). But, in the high luminance driving region over 1,000 cd/m^2, the power efficiency of device W2 is comparable with that of device W1 since the roll-off of device W2 is superior to that of device W1. Especially, considering that it exhibits better driving voltage and luminance characteristics with similar spectral ratios, it seems that our device is worthful to apply for VR and AR applications as OLEDoS base micro-display. As mentioned above, EL spectra of both devices are almost identical each other and it showed sufficiently cool white emission which is suitable for display applications. Detail device performances are summarized in Table 1.

Finally, we verified the color stability in accordance with luminance change to identify our device is appropriate for micro-display. For thorough estimation, we compared color coordinates of each device in CIE 1976 color space. As can be seen in Fig.3(a), the ultra-thin white tandem is comparable to that of the conventional white tandem. It showed stable white emission of (0.155±0.001, 0.492±0.007), while thick white tandem is (0.148±0.002, 0.482±0.002) from 500 cd/m^2 to 2,000 cd/m^2. In addition, it has high color stability as well as tenability. As plotted in Fig.3(b), it showed stable color emission until 10,000 cd/m^2. Consequently, it is verified that the color stability property is also comparable to the conventional tandem white OLEDoS device.

4 CONCLUSIONS

We studied white OLEDoS devices with high luminance at low driving voltage by applying ultra-thin CGU of 10 nm thickness for VR and AR applications. The suggested OLEDoS devices presented relatively high luminance (2,000 cd/m^2) at low driving voltage (6.2 V) compared to the conventional white OLEDoS. Furthermore, it is expected that it has a merit to facilitate the outdoor visibility enhancement in AR applications due to its high luminance property (50,015 cd/m^2 at 10.0 V). In addition, it also promises high color stability which has CIE 1976 color coordinates change of (0.155±0.001, 0.492±0.007) in 500 - 2,000 cd/m^2 luminance region. In conclusion, we anticipate that the suggested white OLEDoS structure is suitable for the current CMOS backplane, thus, it is applicable in VR and AR applications as next-generation micro-displays.

ACKNOWLEDGEMENT

This work was supported by Institute of Information & communications Technology Planning & Evaluation (IITP) grant funded by the Korea government(MSIT) (No. 2020-0-00083, Development of Low MTP Latency Microdisplay and SoC technology for VR·AR devices, and No.2020-0-00867, Display technology development for augmented reality devices with outdoor visibility)

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Table 1. Performances of white OLEDoS device at 2,000 cd/m^2

Device	Driving voltage	Power efficiency	CIE xy
W1	9.9 V	10.5 lm/W	(0.256, 0.376)
W2	6.2 V	10.0 lm/W	(0.272, 0.379)

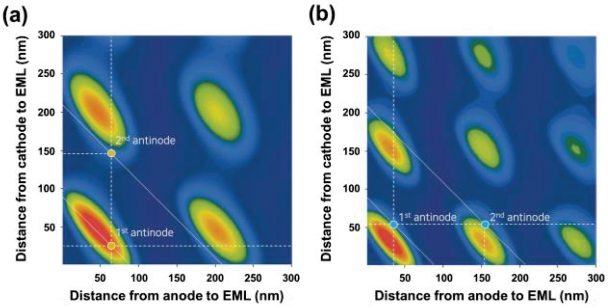

Fig. 1 Optical simulation results of blue and YG OLEDoS device according to the thickness conditions (a) radiance of blue device, (b) radiance of YG device

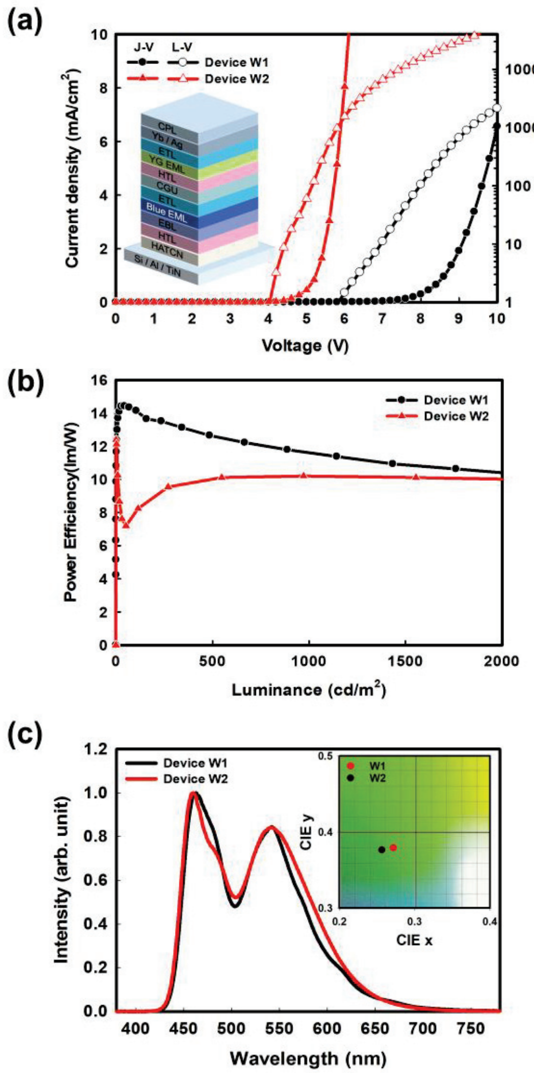

Fig. 2 The performances of fabricated white OLEDoS devices (a) J-V-L characteristics and the structure of devices (inset), (b) power efficiency versus luminance, (c) EL spectra and CIE 1931 color coordinates at 2,000 cd/m^2 (inset)

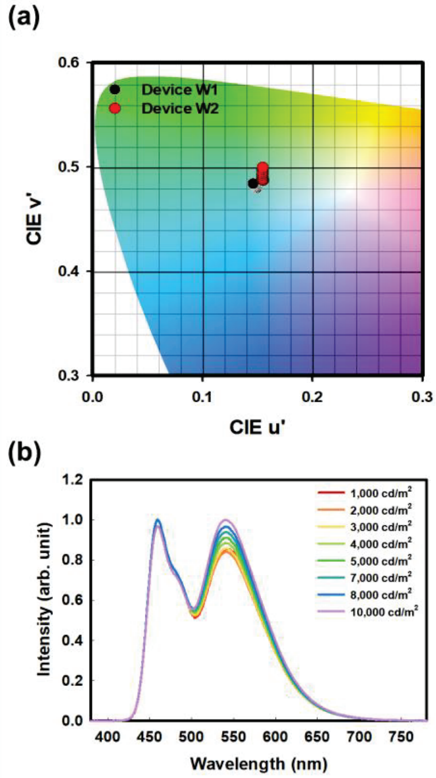

Fig. 3 Color stability properties in accordance with luminance change (a) CIE 1976 color coordinates, (b) EL spectra at each luminance of device W2