White organic light-emitting diode (OLED) microdisplay with a tandem structure

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ABSTRACT
Microdisplay is a key technology for realizing augmented reality (AR) and mixed reality (MR) devices, which have attracted much attention of late. Even though the operating voltage in the tandem structure is higher than that in the single structure, 2-stack tandem OLED exhibited 20,000 cd/m² at 9 V, which is compatible with CMOS circuit driving. Due to its top-emitting geometry with a tandem structure, the OLED device with a well-controlled thickness exhibited a white spectrum with (0.26, 0.26) color coordinates. The pixel density of the fabricated microdisplay panel with a white tandem OLED was about 2350 pixels per inch, and the active area of the panel was 0.7 inch diagonally. The resolution of the panel was 1280 × 1024, corresponding to SXGA, and the maximal luminance was 3,000 cd/m².

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1. Introduction
Augmented reality (AR) and mixed reality (MR) devices are key applications for the future display technology. Liquid crystal on silicon (LCoS) microdisplays were initially applied, but organic light-emitting diode (OLED) microdisplays have attracted much attention [1–3]. Most AR/MR devices have been used in head-mounted or glass-type wearable devices. Hence, thin and lightweight form factor as well as superior image quality are important properties, which are the advantages of the OLED display compared with the LC-based display.

There are two approaches to achieving the OLED microdisplay: using a white OLED structure with a color filter (C/F) and using direct color patterning of evaporating emitters via shadow masks. To realize lively and realistic images, a higher resolution has been essentially demanded in AR/MR devices. From a resolution perspective, the former is more favorable than the latter because the C/F is fabricated via photolithography [1].

The luminance of the microdisplay is another important parameter, especially in AR/MR devices. To ensure visibility outdoors, a minimum of over 2,000 cd/m² luminance is required [3]. Using a white OLED structure with a C/F, however, has a disadvantage for achieving higher luminance because the transmittance of the C/F is not 100% and the blocked light is completely lost. If losses due to the C/F are inevitable, fabricating an efficient white OLED is important. The tandem-structure white OLED has important merits: improved lifetime and efficiency [4]. Theoretically, the current density at a fixed luminance in the tandem OLED is less than that in the single-element OLED, which reduces the device degradation.

A microdisplay was fabricated on an opaque single-crystalline silicon (Si) substrate through complementary metal-oxide-semiconductor (CMOS) processes, which is different from the conventional OLED panels with glass substrates and thin-film transistors (TFTs) [5]. Therefore, to apply a white OLED with a tandem structure, it must be verified that the OLED devices are sufficiently driven by CMOS circuits. In addition, although OLEDs use a top-emitting geometry with a tandem structure, it must be verified that a broadband white emission spectrum is obtained. In this study, a white OLED with a 2-stack tandem structure was applied in the OLED microdisplay. The tandem white OLED exhibited 20,000 cd/m² at 9 V, which is compatible with CMOS circuit driving. The OLED device with a well-controlled thickness exhibited a white spectrum with...
The fabricated microdisplay panel with a white tandem OLED had a 0.7-inch diagonal active area. The resolution of the panel was 1280 × 1024, corresponding to SXGA, and the maximal luminance was 3,000 cd/m².

2. Experiment

The backplanes of the OLED microdisplay panels were fabricated on 8-inch Si wafers by a commercial foundry company, and contained a CMOS integrated circuit (IC)
for OLED microdisplay driving. The 0.11 µm CMOS process was used for the CMOS ICs, and 1.2–5.5 V dual voltages were available [5]. The diced wafer substrates were sequentially cleaned with acetone, methanol, and deionized water, and were transferred to the vacuum thermal evaporator for the deposition of all the organic materials and top cathode metals. A white tandem OLED is shown in Figure 1. The OLED device consists of fluorescent blue and yellow-green phosphorescent emitters connected by a charge generation layer [6]. The fabricated device was encapsulated using ultra-violet (UV)-curable epoxy in an inert-environment glove box. The chip-on-board (COB) bonding process was applied for module packaging. The OLED microdisplay panel was connected to the panel mounting printed circuit board (PCB) through wire bonding. A flexible PCB (FPCB) was used for connecting the OLED microdisplay panel with the driving circuit board. Low-voltage differential signaling (LVDS) was used for the signal interface [5].

The current density (J)-voltage (V) characteristics of the device were measured using a source-measure unit (Keithley-238, Keithley), and the luminance (L) and electroluminescence (EL) spectra were examined using a spectroradiometer (CS-2000, Konica Minolta).

3. Results and discussion

3.1. White emission spectrum of the tandem OLED microdisplay

A top-emitting geometry should be applied in the microdisplay because the OLED device is deposited on an opaque Si wafer. In TEOLEDs, thin-metal-based semi-transparent electrodes are typically used instead of transparent conductive oxides (TCOs), whose deposition can damage the underlying organic layers [7,8]. A certain level of metal film thickness is required to obtain sufficient sheet conductance. At such thickness, the thin metal film has non-negligible reflectance, forming a rather strong microcavity. Therefore, it is important to account for the influence of the microcavity environment on the optical properties of TEOLEDs. In addition, the total organic layer in the tandem structure is more than twice as thick as that in the single structure, resulting in a stronger microcavity environment [9].

When designing the device structure, optical simulation was conducted to obtain the guidelines for the approximate thickness. Assuming the simplified structure as shown in Figure 2(a), the change of the spectrum according to the thickness of the organic layer between two emitters was confirmed via optical simulation. The thicknesses of the electron transport layer (ETL) and hole transport layer (HTL) for the simplified model were assumed to be 30 and 60 nm, respectively, for

Figure 3. J-V characteristics of YG single OLEDs for different HILs.

Figure 4. J-V characteristics of tandem OLEDs for (a) different Yb thicknesses and (b) the ETL structure. The inset figure shows the transmittance of the Yb/Ag bilayer.
the blue and yellow-green cavity length. As the thickness of the organic layer between the two emitters increases, the cavity length of the OLED device also increases. The increased cavity length leads to the red shift of the resonance wavelength. As a result, cool white emission spectra can be obtained when the blue emission is enhanced, but the yellow-green emission is suppressed, as shown in Figure 2(b).

Figure 2(c) shows the emission spectra of the tandem OLEDs for different HTL thicknesses in a blue-emitting unit. The trend of spectral change is similar to the simulation result. The CIE coordinates of tandem OLEDs with a 20-nm-thick HTL are (0.270, 0.290). When the HTL thickness increases by 10 nm, the CIE coordinates of tandem OLEDs change to (0.292, 0.398), (0.314, 0.499), and (0.318, 0.541), as shown in Figure 2(b). As the thicknesses of other organic layers are less than 40 nm, it is not possible to reduce the total organic layer thickness. In other words, a white emission spectrum is obtained at the minimum thickness to form a tandem structure. If the total organic layer thickness further increases, it will be hard to obtain broad band emission.

3.2. Lowering the operating voltage of tandem OLEDs

The silver (Ag)/indium tin oxide (ITO) bilayer is widely used as a bottom electrode for top-emitting OLEDs owing to the high reflectance of Ag and the high work function of ITO [10]. These materials, however, are not currently available in the general CMOS foundry. Instead, an aluminium (Al)/titanium nitride (TiN) bilayer compatible with the CMOS process is used as the bottom electrode for the OLED microdisplay [11]. Al contributes to low sheet resistance and high reflectance, and TiN contributes to the proper work function for using an anode in OLEDs [12]. To lower the operating voltage of tandem OLEDs, the selection of a hole injection layer (HIL) is important to efficiently inject holes from TiN to the HTL.

Figure 3 shows the J-V characteristics of single OLED devices. To focus on the hole injection property from the Al/TiN anode, a single OLED structure based on the YG unit in the tandem OLED structure was used. Compared with Dipyrazino[2,3-f:2′,3′-h] quinoxaline-2,3,6,7,10,11-hexacarbonitrile (HAT-CN), widely used as a hole injection material in OLEDs, the p-doping HIL showed a larger J at the same V. When the doping ratio was optimized as 15%, the operating voltage was reduced from 4.5–3.4 V at the J of 10 mA/cm².

Efficient electron injection from the top cathode is also significantly important. For the top-emitting geometry, any terbium (Yb)/Ag bilayer was used in this study because Ag alone is not favorable for injecting electrons into an ETL. Figure 4(a) shows the J-V characteristics of the tandem OLED for different Yb thicknesses. As the
Yb thickness increases, the electron injection property is enhanced, but the transmittance of the bilayer cathode decreases, as shown in the inset in Figure 4(a). Due to the trade-off between the electron injection property and the cathode transmittance, the change in the Yb thickness is not suitable for decreasing the operating voltage while maintaining the same luminance. Therefore, a method capable of improving electron injection while minimizing the thickness of Yb is required. As applied in the p-i-n OLED structure [13], an ETL/n-doped ETL was applied while maintaining the same thickness as the ETL single layer. Figure 4(b) shows the J-V characteristics of the tandem OLED devices for a different ETL structure. When the n-doping ETL replaced some ETL thicknesses, the operating voltage was reduced from 9.6–8.7 V at the J of 100 mA/cm².

3.3. White OLED microdisplay panel

The 2-stack tandem OLED exhibited 20,000 cd/m² at 9 V, which is compatible with CMOS circuit driving, as shown in Figure 5(a). The well-controlled OLED structure exhibited a white spectrum with (0.26, 0.26) CIE coordinates and 28 cd/A current efficiency at 1,000 cd/m², as shown in Figure 5(b). Figure 5(c) shows the operating image of the fabricated microdisplay panel with white tandem OLED. The pixel density was about 2350 pixels per inch, and the active area of the panel was 0.7 inch diagonally. The resolution of the panel was 1280 × 1024, corresponding to SXGA, and the maximal luminance was about 3,000 cd/m².

4. Conclusion

A white organic light-emitting diode (OLED) microdisplay with a tandem structure was successfully demonstrated. In spite of its top-emitting geometry with a tandem structure, a white emission spectrum was obtained through well-controlled cavity design. In addition, by using p- and n-doped organic layers as the HIL and electron injection layer (EIL), respectively, the operating voltage of the tandem OLEDs was sufficiently reduced for CMOS circuit driving. The fabricated OLED microdisplay had a 0.7 inch size and an SXGA resolution.

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References

[1] T. Fujii, C. Kon, Y. Motoyama, K. Shimizu, T. Shimayama, T. Yamazaki, T. Kato, S. Sakai, K. Hashikaki, K. Tanaka, and Y. Nakano, 46-3: Distinguished Paper: 4032ppi High-Resolution OLED Microdisplay, SID Digest. 49 (1), 613–616 (2018).

[2] P. Wartenberg, M. Buljan, B. Richter, G. Haas, S. Brenner, M. Thiemle, U. Vogel, and P. Benitez, 40-5: Invited Paper: High Frame-Rate 1” WUXGA OLED Microdisplay and Advanced Free-Form Optics for Ultra-Compact VR Headsets, SID Digest. 49 (1), 514–517 (2018).

[3] A. Ghosh, E.P. Donoghue, I. Khayrullin, T. Ali, I. Wacyk, K. Tice, F. Vazan, O. Prache, Q. Wang, L. Sziklas, D. Fellowes, and R. Draper, 18-1: Invited Paper: Ultra-High-Brightness 2K x 2K Full-Color OLED Microdisplay Using Direct Patterning of OLED Emitters, SID Digest. 48 (1), 226–229 (2017).

[4] H. Kanno, R.J. Holmes, Y. Sun, S. Kena-Cohen, and S.R. Forrest, White Stacked Electrophosphorescent Organic Light-Emitting Devices Employing MoO3 as a Charge-Generation Layer, Adv. Mater. 18, 339–342 (2006).

[5] H. Lee, H. Cho, C.-W. Byun, C.-M. Kang, J.-H. Han, J.-I. Lee, H. Kim, J.H. Lee, M. Kim, and N.S. Cho, Device Characteristics of Top-Emitting Organic Light-Emitting Diodes Depending on Anode Materials for CMOS-Based OLED Microdisplays, IEEE Photonics J. 10 (6), 8201809 (2018).
[6] H. Cho, C.W. Joo, J. Lee, H. Lee, J. Moon, J.-I. Lee, J.Y. Lee, Y. Kang, and N.S. Cho, Design and Fabrication of Two-Stack Tandem Type All-Phosphorescent White Organic Light Emitting Diode for Achieving High Color Rendering Index and Luminous Efficacy, Opt. Express 24 (21), 24161–24168 (2016).

[7] H. Riel, S. Karg, T. Beierlein, W. Rieß, and K. Neyts, Tuning the Emission Characteristics of Top-Emitting Organic Light-Emitting Devices by Means of a Dielectric Capping Layer: An Experimental and Theoretical Study, J. Appl. Phys. 94 (8), 5290–5296 (2003).

[8] Q. Huang, K. Walzer, M. Pfeiffer, V. Lyssenko, G. He, and K. Leo, Highly Efficient Top Emitting Organic Light-Emitting Diodes with Organic Outcoupling Enhancement Layers, Appl. Phys. Lett. 88, 113515 (2006).

[9] H. Cho, J. Song, B.-H. Kwon, S. Choi, H. Lee, C.W. Joo, S.-D. Ahn, S.-Y. Kang, S. Yoo, and J. Moon, Stabilizing Color Shift of Tandem White Organic Light-Emitting Diodes, J. Ind. Eng. Chem. 69, 414–421 (2019).

[10] M.J. Park, S.K. Kim, R. Pode, and J.H. Kwon, Low Absorption Semi-Transparent Cathode for Micro-Cavity Top-Emitting Organic Light Emitting Diodes, Org. Electron. 52, 153–158 (2018).

[11] Y. Ji, F. Ran, H. Xu, W. Shen, and J. Zhang, Improved Performance and Low Cost OLED Microdisplay with Titanium Nitride Anode, Org. Electron. 15, 3137–3143 (2014).

[12] V. Adamovich, A. Shoustikov, and M.E. Thompson, TiN as an Anode Material for Organic Light-Emitting Diodes, Adv. Mater. 11 (9), 727–730 (1999).

[13] M. Pfeiffer, S.R. Forrest, K. Leo, and M.E. Thompson, Electrophosphorescent p–i–n Organic Light-Emitting Devices for Very-High-Efficiency Flat-Panel Displays, Adv. Mater. 14, 1633–1636 (2002).