Recent progress of organic light-emitting diode microdisplays for augmented reality/virtual reality applications

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ABSTRACT

Microdisplays have been used in various applications such as beam projectors, view finders of digital cameras, projection TVs, night vision for military use, and augmented reality/virtual reality (AR/VR) devices. Organic light-emitting diode (OLED) microdisplays have attracted much attention as main displays of glass-type and head-mounted-type AR/VR devices due to their rich colors, high contrast ratio, fast response time, small form factor, and high resolution. This review investigates the device, process, pixel circuit, and panel technologies for OLED microdisplays. In addition, the technology status and issues of OLED microdisplays are discussed.

1. Introduction

Microdisplays have received much attention as main display engines of augmented reality/virtual reality (AR/VR) devices due to their small size and high resolution [1–4]. There are many types of microdisplays such as liquid crystal display (LCD)-based microdisplays that use high-temperature polysilicon (HTPS) technology [5], liquid crystal on silicon (LCoS) [4,6], digital micromirror device (DMD) [6,7], organic light-emitting diode (OLED)-based microdisplays including OLED on silicon (OLEDoS) [8–16], quantum dot-based microdisplays [17], and microLED-based microdisplays [18,19]. LCoS and DMD have already been used in various applications such as projectors, projection TVs, night vision for military use, and AR/VR glasses. LCoS microdisplays have high luminance and simple fabrication processes, but low response time, low contrast ratio, and relatively large volume and weight due to their external lighting sources. DMD microdisplays have a complex fabrication process and need additional light sources. Advanced technologies are required for high-resolution and low-cost full-color quantum dot-based and microLED-based microdisplays.

OLED microdisplays have been used in various electronic devices such as TVs, mobile phones, tablets, laptops, and automotive displays due to their fast response time, small thickness, light weight, high contrast ratio, rich colors, and small form factor. Because OLED microdisplays have superior performance compared with LCoS and DMD microdisplays, many AR/VR devices use OLED microdisplays [1,2]. However, even though OLED microdisplays have been released commercially, they need much higher luminance, resolution, and efficiency to improve the device quality. Since the first OLED microdisplays were developed in the late 1990s [8,9], OLED microdisplay technology has been rapidly improving. After the company eMagin, which pioneered OLED microdisplays, released its SVGA product in the market in 2001, many companies such as MicroOled (France), Sony (Japan), OlighTek (China), Kopin (USA), Seeya (Chian), and LG Display (South Korea) emerged and researched and sold OLED microdisplays. To increase the applications and market share of OLED microdisplays, their device architectures, materials, and fabrication processes should be improved. In addition, the size of the OLED microdisplay panel must be expanded for a wide field of view (FoV) in AR/VR glasses. A stepper is generally used for high-resolution pixel patterning in microdisplays, and its one-shot size is approximately 1 inch diagonally. Therefore, a stitching process is required for over 1-inch microdisplay panels, but it is a very difficult process for achieving high image quality. Consequently, some innovative technologies are required for large and high-resolution microdisplay panels.
Red (R), green (G), and blue (B) subpixels are required for full-color OLED microdisplays. There are two typical methods of R, G, and B patterning (Figure 1). The first method is direct patterning using fine metal masks (FMMs). The FMMs are used to separately pattern the R, G, and B emitting layers (EMLs). This method is advantageous for high luminance, efficiency, and color gamut. Recent OLED panels for mobile phones use the FMM process for R, G, and B patterning. However, the FMM process is very difficult to apply to microdisplays because the subpixel size of microdisplays is as small as a few micrometers. Fabrication of the thin FMM with a very tiny hole and accurate alignment for arranging the R, G, and B subpixels with a high yield are still technological obstacles for FMM-based OLED microdisplays. Another method of realizing a full-color microdisplay is with the use of a white OLED with color filters (CFs). Although this method decreases the luminance and efficiency of the OLEDs, the photolithography-based CF patterning process makes available over 2,000 pixels per inch (ppi). Consequently, most OLED microdisplay panels use this process for realizing full color. However, only 1/3 light from the white emission is used and others are lost, resulting in low efficiency and luminance. Therefore, high-performance white OLEDs are needed for high-luminance and high-efficiency full-color OLED microdisplays.

In this review, we provide an overview of the progress achieved in the development of OLED microdisplays. First, device structures and processes in OLED microdisplays, which include top metal electrodes, the pixel patterning process, high luminance technology, and color conversion structures, are discussed in section 2. Then OLED microdisplay panel technologies for various applications are introduced in section 3. Finally, the challenges and prospects of OLED microdisplays are summarized in section 4.

2. Device structures and processes in OLED microdisplays

2.1. Top metal electrodes

OLED microdisplays need many pixels in very small panels for excellent image quality. Conventional thin-film transistor (TFT)-based glass substrates limit the pixel size due to the low charge mobility and aperture ratio of TFTs. Most OLED microdisplays use complementary metal–oxide–semiconductor (CMOS)-based Si wafers because CMOS-based transistors have high charge carrier mobility and can be very small, which can allow the inclusion of an integrated circuit (IC) in the display panel. However, the Si wafer is opaque, and the CMOS process has limited available metals. Therefore, conventional device structures and processes should not be used for the OLED structure and process. Many studies have been conducted on top metal electrodes on Si wafers for OLED microdisplays. In 2006, Kreye et al. used aluminum (Al) and titanium nitride (TiN)/Al as top metal electrodes on CMOS substrates for OLED microdisplays [20]. Because Al was commonly used as a cathode, the n-i-p structure was used as shown in Figure 2(a). However, the device showed a high driving voltage of 8.5 V at 100 cd/m². This could have been due to the native oxide layer on top of the Al cathode, which might have disturbed the electron injection from the Al cathode to the electron transport layer (ETL). To solve this problem, TiN-coated Al electrodes with a p-i-n structure were used, as shown in Figure 2(b). TiN is a good top metal electrode candidate because it has CMOS process properties, proper work functions for hole injection, and a smooth surface morphology. However, the TiN layer should be thin, because the thicker it is, the more rapidly its optical reflectivity for blue light is reduced. The R, G, and B OLED that uses TiN electrodes showed driving voltages of 4.85, 3.2, and 4.4 V.

Figure 1. Schematic structures of (a) the separately patterned R, G, and B EMLs and (b) the white OLED with R, G, and B CFs for full-color OLED microdisplays.
Figure 2. Schematic pixel structure with (a) an Al top metal and n-i-p [20]. Reprinted with permission from ref. [20]. Copyright 2006, SPIE. (b) TiN top metal and p-i-n structure [20]. Reprinted with permission from ref. [20]. Copyright 2006, SPIE. (c) Reflectance and sheet resistance of anodes I and II [21]. Reprinted with permission from ref. [21]. Copyright 2012, John Wiley and Sons. (d) Luminance efficiency of OLEDs with different anodes [21]. Reprinted with permission from ref. [21]. Copyright 2012, John Wiley and Sons. (e) Schematic pixel structure with five-layer top metal anodes [22]. Reprinted with permission from ref. [22]. Copyright 2014, Elsevier. (f) SEM image of the pixels and the fabricated monochromatic OLED microdisplay [22]. Reprinted with permission from ref. [22]. Copyright 2014, Elsevier. (g) Reflectance of CMOS-processed various top metal electrodes [23]. Reprinted with permission from ref. [23]. Copyright 2018, IEEE. (h) Fabricated SXGA green OLED microdisplay from the Electronics and Telecommunications Research Institute [23]. Reprinted with permission from ref. [23]. Copyright 2018, IEEE. (i) Luminance-voltage characteristics of OLEDs with differently processed Al electrodes [24]. Reprinted with permission from ref. [24]. Copyright 2020, Taylor & Francis. (j) The fabricated SVGA green OLED microdisplay [24]. Reprinted with permission from ref. [24]. Copyright 2020, Taylor & Francis.
at 100 cd/m², respectively. In 2009, Ali et al. also compared two anodes with different reflectance and sheet resistance values for OLED microdisplays, as shown in Figure 2(c) [21]. Although they did not disclose used anode materials, they demonstrated high-performance top-emitting green OLEDs with anode II, which had a high luminance efficiency of 80 cd/A, as shown in Figure 2(d). In addition, the projected operating half-lifetime of the device with anode I was 36,000 h with an initial luminance of 1,000 cd/m², which implies that fabricated devices can be available for practical applications. Ji et al. used a five-layer sandwich structure of Ti/TiN/Al/Ti/TiN layers as a top metal anode for OLED microdisplays, as shown in Figure 2(e) [22]. The bottom Ti layer helped the metal Al to adhere to the insulating layer, and the upper Ti layer reduced the sheet resistance of the top metal. The Semiconductor Manufacturing International Corporation (SMIC, China) 0.35 μm 3.3–6 V dual-voltage standard CMOS process and a seven-transistor voltage pulse width modulation (PWM) pixel drive circuit were applied for the 5 × 15 μm subpixel size. The resolution and diagonal size of the fabricated monochromatic OLED microdisplay were 1280 × 3 × 1024 and 0.97 inch, respectively, as shown in Figure 2(f). Lee et al. compared three different top metal electrodes—Al/TiN, Ti, and tungsten (W)—for OLED microdisplays [23]. The Al/TiN electrode had much higher reflectance than other metal electrodes, and its reflectance increased as the thickness of the TiN decreased, as shown in Figure 2(g). The W electrode showed a good hole injection property because the W was naturally oxidized to WO₃ and the WO₃ had high work function, with which it could easily inject holes into the hole-injection layer (HIL). Based on the OLED device results, an SXGA green OLED microdisplay was fabricated with a diagonal size of 0.7 inch. The 0.11 μm CMOS process was used and the sub-pixel size was 3.6 × 10.8 μm. Xue et al. also reported that the Al electrode that was fabricated using the standard CMOS processes after chemical mechanical polishing (CMP) had residual organic contaminants and a thin Al oxide layer on the surface, which were seen using x-ray photoelectron spectroscopy, as shown in Figure 2(i) [24]. They demonstrated a green SVGA OLED microdisplay with a pixel size of 15 × 15 μm, as shown in Figure 2(j).

2.2. Pixel patterning process

Subpixel patterning is one of the critical issues in full-color OLED microdisplays because a very small pixel pitch is required for high resolution. The conventional patterning method, which uses a white OLED with CFs, decreases the luminance and efficiency of OLEDs. Many researchers focus on direct patterning of the R, G, and B EMLs without CFs for improved luminance and efficiency of OLED microdisplays. In 2013, Herold et al. developed the Flash-Mask-Transfer-Lithography (FMTL) technology for fabricating small and differently colored OLED subpixels on a silicon substrate [25]. As shown in Figure 3(a), the patterned reflectors and absorbers defined the pixel layout, and the organic materials for one color were deposited on top of the FMTL mask. The part that absorbed the thermal energy was transferred to the target substrate. This method realized lines with feature sizes down to 10 μm, as shown in Figure 3(b). However, they did not show the full-color OLED microdisplays using the FMTL technology. In 2016, Ghosh et al. from eMagin company developed the first full-color OLED microdisplays using direct patterning of the R, G, and B EMLs, as shown in Figure 3(c) [26]. The RGB directly patterned display showed much higher luminance than the display with a white OLED and CFs [26]. OLED microdisplays with a 882 ppi VGA resolution and a 2,645 ppi WUXGA resolution were demonstrated as shown in Figure 3(d). In addition, 2K × 2K full-color OLED microdisplays were developed using the direct patterning method in 2017 [27]. The diagonal viewing area of the panel was 1.06 inch, and the maximum luminance was 5,000 cd/m². The panel used an RGBG pixel structure and showed a 133% sRGB color gamut. Malinowski et al. reported high-resolution photolithography for direct-view active-matrix OLED (AMOLED) AR displays [28]. They demonstrated 1 μm OLED patterns, as shown in Figure 3(e), and the T90 lifetime of a green phosphorescent OLED that used this patterning method was over 150 h at the starting luminance of 1,000 cd/m². They archived a two-color 1,250 ppi passive matrix (PM) OLED display and a semi-transparent green AMOLED display using the photolithography process, as shown in Figure 3(f) and (g), respectively. In 2020, Mu et al. developed electrohydrodynamic (EHD) printing for high-resolution OLED displays [29]. They investigated printability depending on solvents and obtained polymer line widths of 1.5 μm for R, 1.7 μm for G, and 1.6 μm for B, as shown in Figure 3(h). Moreover, they fabricated 2,115 ppi monocolor PM polymer displays with a display size of 3.5 × 2.3 mm² using their patterning method, as shown in Figure 3(i). Ventsch et al. reported on solution-processed top-emitting OLEDs, which can be applied to full-color microdisplays [30]. Their polymeric emitters are crosslinkable and can be patterned in the UV-lithography process. The R, G, and B polymers can be patterned to 2 μm, as shown in Figure 3(j), and allow full color in OLED microdisplays using direct patterning instead of a white OLED with CFs [31].
2.3. Device structures for high luminance

High luminance is a very important factor of outdoor display applications but a weak point of OLED microdisplays. A tandem structure stacks OLED units and thus, generally increases the luminance and current efficiency of OLED devices [32]. However, it needs higher driving voltages as the number of OLED units stacked increases. For a high driving voltage, the size of the transistor should be increased, but a large transistor decreases the pixel density of the display panel. In 2019, Cho et al.
adopted a two-stack white tandem structure for OLED microdisplays, as shown in Figure 4(a) [33]. They optically optimized a device structure using optical simulation and reduced the driving voltage using p- and n-doped transporting layers. Although an electrical doping method typically improves the performance of OLEDs [33,34], the electrical crosstalk of the subpixels should be considered when the doping concentration is determined due to the very small pixel pitch in OLED microdisplays. Their white device exhibited a maximum luminance of 20,000 cd/m² at 9 V, and a white OLED microdisplay that had a 2,350 ppi resolution with a maximum luminance of 3,000 cd/m² was demonstrated, as shown in Figure 4(b). In 2020, Hamar et al. also applied a tandem structure to OLED microdisplays [35]. They demonstrated OLED microdisplays using three-, four-, and five-stack tandem structures, as shown in Figure 4(c). As the stack number increases, the lifetime of OLEDs is dramatically enhanced, as shown in Figure 4(d). Their panel resolution was WUXGA and the RGBW pixel structure was used for higher luminance due to the unfiltered white subpixel.

A light extraction structure can also improve the luminance and efficiency of OLED microdisplays [36]. However, such structure is very challenging to use in OLED microdisplay panels due to their very tiny pixel size and the top-emitting structure of OLEDs. R. Pfeifer et al. optically simulated the OLED structure with nanostructured substrates for OLED microdisplays, as shown in Figure 4(e) [37]. The grating was inserted between the Al-based anode and the HTL and consisted of SiO₂ and doped amorphous silicon. The outcoupling efficiency was changed depending on the period and height of the grating and could be enhanced to up to 35% compared to the same structure without grating. In 2019, Motoyama et al. developed high-efficiency OLED microdisplays using microlens arrays [38]. The microlens array was fabricated on the CF, and the microlens/CF-coated glass substrate was assembled into the OLED substrate with high paring accuracy, as shown in Figure 4(f). The microlens array showed 1.8 times enhanced luminance without wavelength dependency and improved the current efficiency and the color shift of the viewing angle. In addition, they used InZnO as a semi-transparent top cathode instead of the typical MgAg cathode, which improved the efficiency 1.3 times compared to the MgAg structure. Consequently, they successfully demonstrated the 0.23” nHD OLED microdisplay with a high luminance of 5,000 cd/m² by developing the microlens array and the InZnO cathode, and optimizing the spectral transmittance of the CF, as shown in Figure 4(g).

2.4. Color conversion structures

Full color in displays can be realized using a color conversion layer with blue light sources [39]. Blue OLEDs can be used as blue light sources and have a much simpler structure than white OLEDs. Ghosh et al. tested color-changing materials (CCMs) for OLED microdisplays, as shown in Figure 5(a) [40]. They compared CCMs processed via spin-coating and vacuum-depositing and found that only vacuum-deposited films satisfied the requirements for OLED microdisplays. In addition, crosstalk and color bleeding are critical issues in OLED displays that use CCMs or CFs. To decrease the crosstalk problem, the gap between the display and the CCMs or CFs should be reduced, as shown in Figure 5(b), and the space distribution of the OLED emission should be narrow, using the microcavity effect. In 2020, Kim et al. reported the R, G, and B color generation method from white top-emitting OLEDs by applying a cavity control layer, as shown in Figure 5(c) [41]. InZnO was used as a cavity control layer, and the R, G, and B colors were easily realized without CFs or R, G, B EMLs by changing the thickness of the cavity control layer. However, there was a blue emission leakage in the red color device due to its cavity condition. Silver nanoparticles-doped ETL and rubrene-doped HTL were used to suppress such blue emission leakage, as shown in Figure 5(d).

3. OLED microdisplay panel technology for various applications

3.1. High-resolution displays using advanced TFT processes for VR applications

Due to their intrinsic small size, OLED microdisplays can be applied to head-mounted or glass-type AR/VR devices. In head-mounted devices for VR applications, large and high-resolution displays are preferred to improve the FoV and the immersiveness. However, a display size of over 1 inch is difficult to achieve using the conventional CMOS technology with a stepper. Fortunately, the large display size mitigates the design rules up to a few micrometers, enabling the application of the TFT process on the glass substrates with advanced technology. To apply the TFT process, the pixel circuit should be simplified due to the small pixel size. As shown in Figure 6(a), Keum et al. proposed an OLED pixel circuit that consisted of three TFTs (3T) and two capacitors (2C) using the simultaneous emission driving method with a low crosstalk error of less than ±1 least significant bit (LSB) [42]. Using the proposed pixel structure, they demonstrated the 5.87-inch, 1,000 ppi, and 5,120 × 2,880-resolution low-temperature
Figure 4. (a) Structure of the white tandem OLED microdisplay [33]. Reprinted with permission from ref. [33]. Copyright 2019, Taylor & Francis. (b) Operating image of the fabricated white OLED microdisplay panel [33]. Reprinted with permission from ref. [33]. Copyright 2019, Taylor & Francis. (c) Comparison of images in displays made with three-, four-, and five-stack OLEDs [35]. Reprinted with permission from ref. [35]. Copyright 2020, John Wiley and Sons. (d) Lifetime versus OLED-display power at 1,000 cd/m² flat fields of the D65-peak white OLED microdisplay [35]. Reprinted with permission from ref. [35]. Copyright 2020, John Wiley and Sons. (e) The top-emitting OLED stack without grating (left) and with grating (right) [37]. Reprinted with permission from ref. [37]. Copyright 2011, IEEE. (f) High-efficiency OLED device structure with a microlens [38]. Reprinted with permission from ref. [38]. Copyright 2019, John Wiley and Sons. (g) Photograph of 0.23” nHD and 0.7” FHD OLED microdisplay displays [38]. Reprinted with permission from ref. [38]. Copyright 2019, John Wiley and Sons.

Figure 5. (a) Cross-section of an OLED display sealed with the CCM/C/F substrate [40]. Reprinted with permission from ref. [40]. Copyright 2012, John Wiley and Sons. (b) Effect of the gap between the display and the CCM and/or CF substrates on the OLED display contrast ratio [40]. Reprinted with permission from ref. [40]. Copyright 2012, John Wiley and Sons. (c) Device structure of the fabricated R, G, and B TEOLED with variation of the cavity control layer [41]. Reprinted with permission from ref. [41]. Copyright 2020, Elsevier. (d) EL spectra with suppressed B emission characteristics of WTEOLED [41]. Reprinted with permission from ref. [41]. Copyright 2020, Elsevier.
Figure 6. (a) The 3T-2C pixel circuit for AR/VR applications [42]. Reprinted with permission from ref. [42]. Copyright 2018, John Wiley and Sons. (b) Aperture ratios of the conventional and developed pixels with regard to the pixel density [44]. Reprinted with permission from ref. [44]. Copyright 2018, John Wiley and Sons. (c) The vertically stacked oxide TFT for the high-resolution AMOLED [45]. Reprinted with permission from ref. [45]. Copyright 2020, John Wiley and Sons. (d) Image of the 0.62-inch, 2,351 ppi AMOLED panel using the stacked oxide TFT [46]. Reprinted with permission from ref. [46]. Copyright 2019, John Wiley and Sons.

polycrystalline silicon (LTPS)-based AMOLED display panel with a magnifying glass lens for VR applications. Yu et al. also introduced a simple pixel circuit of 3T-1C for high-resolution displays [43]. Different pixel circuits for the p-type metal–oxide-semiconductor (PMOS) and the n-type metal–oxide-semiconductor (NMOS) were developed to consider both the functions and the process capacity. By developing the pixel circuits, TFT processes, and driving schemes, they demonstrated both the 3.23-inch, 1,000 ppi, 2,160 × 2,400-resolution, and 90 fps PMOS display panel and the 2.2-inch, 1,000 ppi, 1,080 × 2,400-resolution, and 120 fps NMOS display panel. Cheng et al. developed the circuitry for a high-resolution AMOLED panel that included a pixel circuit to compensate for the threshold voltage (VTH) variation and the voltage drop, and a gate driver on an array that generated S and E waveforms [44]. To reduce the screen-door effect, the high-resolution OLED patterning process was also developed, which resulted in a high aperture ratio of 17% with a pixel size of 11.4 μm, as shown in Figure 6(b). By integrating the frontplane and backplane technologies, they demonstrated the 2.17-inch, 2,228 ppi AMOLED panel for near-eye applications.

The aforementioned studies used the LTPS TFT technology. Another mainstream of TFT technology is the oxide TFT, which exhibits high productivity and uniformity. However, the lower mobility of the oxide TFT compared to the LTPS TFT leads to a large TFT size for pixel driving, which is an obstacle to its application to high-resolution displays. To solve this problem, Lee et al. developed the vertically stacked oxide TFT backplane technology for high-resolution displays [45]. Due to the double TFT layers, the TFT size, line width, gap between the metal lines, and via size can be increased, reducing the short channel effect and the RC delay and improving the uniformity. As shown in Figure 6(c), with the TFT channel length of 4 μm, a vertically stacked TFT array that corresponded to a 1.2-inch, 1,360 ppi, and 1,370 × 890-resolution AMOLED backplane was fabricated. Shishido et al. also reported a stacked oxide TFT with a channel length of 0.36 μm [46], in which the 4T-2C pixel circuit was separated into 2T and 1C, each of which was located at the upper and lower layers, enabling a 1.7 times increase in the pixel density. Using the stacked structure, they demonstrated the 0.62-inch, 2,351 ppi, and 1,280 × 720-resolution full-color AMOLED panel shown in Figure 6(d).

3.2. High-performance OLED microdisplays for small-form-factor AR devices

For glass-like small-form-factor AR devices, the display size should be reduced. To improve the performance of a device with a small form factor, a high pixel density display is required, which is technically challenging for both the frontplane and backplane points of view. To drive
OLED with high luminance, a high current should be supplied through the pixel circuit, which will result in a large transistor size with a high breakdown voltage. In addition, the small pixel pitch also decreases the width of the signal line, leading to power loss and increased RC delay. That is, there is a trade-off between the high resolution and the brightness, power consumption, and frame rate. The gap between the CF and the white OLED should also be decreased to reduce the optical crosstalk for the small pixel size. As the adjacent subpixel has a different color, the optical crosstalk deteriorates the color purity. Thus, to realize high-performance OLED microdisplays with a high pixel density, the overall technology, including the process, structure, pixel circuit, and driving scheme, should be developed. Fujii et al. developed front-plane and backplane technologies for 4,032 ppi OLED microdisplays [47]. To reduce the pixel size, they optimized the 4T-2C pixel circuit and the pixel driving circuits. Each transistor size was carefully designed by considering the $V_{TH}$ variation, breakdown voltage, and driving current in the process development. For the front-plane, an on-chip CF(OCCF) process was developed to improve the viewing angle of the chromaticity. As shown in Figure 7(a), the OCCF structure with RBGB pixel arrangement exhibited low angle chromaticity variation. For low power consumption and high-speed driving, they designed low-voltage-driven peripheral analogue circuits and high-voltage-driven pixel driving circuits, respectively. The newly designed driving scheme, which was dual-line progressive with bundled lines shifting, realized 240 frame rates with suppressed degradation of resolution, as shown in Figure 7(b). Through the overall technology improvements, they demonstrated the high-performance 0.5-inch, 4,032 ppi, and $1,600 \times 1,200$-resolution OLED microdisplay. Lu et al. reported the 5,644 ppi OLED microdisplay with 4.5 μm pixel through subpixel rendering [48]. Using the normal delta pixel arrangement with embedded image enhancement functions and an OCCF structure, they demonstrated the 0.39-inch, 5,644 ppi, and $1,920 \times 1,080$-resolution OLED microdisplay. Katsui, Shishido et al. reported the oxide-transistor-based 5,291 ppi microdisplay by using c-axis aligned crystalline In–Ga–Zn–O (CAAC-IGZO) field effect transistors (FETs) with a channel length of 60 nm [49,50]. As shown in Figure 7(c), the IGZO FET has a tri-gate structure to improve the electric field control through the gate [49]. The 60-nm FET exhibited a high breakdown voltage of more than 10 V, suitable current capability and saturation characteristics, and an extremely low off-state current of below 1 pA, which enabled the application of the FET to high-resolution OLED displays. The 2T-1C pixel circuit and the RGB zigzag arrangement were adopted for high resolution. Using the 60-nm CAAC-IGZO FETs, a 0.28-inch, 5,291 ppi, and $1,280 \times 720$-resolution OLED microdisplay was demonstrated.
To implement small-form-factor AR devices, not only a small microdisplay but also a simple optical system is required. Lee et al. reported an OLED microdisplay combined with a pin mirror lens-based optical system [51]. They implemented the AR device by combining only the thin pin mirror lens and the OLED microdisplay. In addition, the horizontal FoV of the AR device was improved to 43° using a high-aspect-ratio (32:9) OLED microdisplay with a laterally expanded pin mirror array, as shown in Figure 8(a). Another approach to reducing the form factor of an AR device is by using a curved display, which makes the optical system simpler and lighter [52,53]. To fabricate the curved OLED microdisplay, the mechanical grinding process was used [52]. After grinding, the thickness of the OLED microdisplay decreased to 70–130 μm, even as the electro-optical characteristics of the OLED were maintained. After the one-dimensional bending process, OLED microdisplays with a curvature radius of 45 mm, a 0.38-inch WVGA, and a 1-inch WUXGA were demonstrated, as shown in Figure 8(b). In addition, a visual system that uses a curved microdisplay can reduce the system volume by 29.1% compared to a system that uses a flat microdisplay [53]. Fraunhofer Institute reported image sensor-integrated OLED microdisplays in 2009 [54–59]. As shown in Figure 8(c), the RGBW light emitters and photodetector were arranged in the same panel, displaying images and detecting light simultaneously. Using the integrated image sensor, they successfully produced 800 × 600-resolution eye images, which can be applied to eye-tracking in AR/VR applications. No additional camera or sensor is needed for eye tracking, which helps reduce the size of small-form-factor devices.

Some applications, especially with high activity, may need a slim and light AR device rather than a device with a high-quality display. In such applications, the microdisplay may not need to be full-color and high-resolution and to have a high frame rate but may need to be small and with low power consumption. Vogel et al. reported an ultra-low-power OLED microdisplay for wearable visualization [58–60]. A highly efficient green monochrome OLED device was designed and fabricated, which resulted in a maximum current efficiency of 47.7 cd/A at 1,000 cd/m². To reduce the power
consumption for display driving, the in-pixel memory structure and the freely addressable matrix technique were developed. In this structure, only the image-changing pixels can be updated, enabling safe driving especially in idle mode. As shown in Figure 8(d), using the highly efficient OLED and low-driving-power pixel circuits, the 0.19-inch, 304 × 256-resolution, and low-power-consumption (10–40 mW) OLED microdisplay was demonstrated. The OLED microdisplays and their characteristics published to date are summarized in Table 1.

4. Summary and perspective

OLED microdisplay technology has rapidly developed due to its potential for various applications. Various top metal electrodes, tandem OLED architectures, and light extraction structures have been studied and used to enhance the efficiency and luminance of OLED microdisplays. In addition, novel color patterning processes and color conversion structures have been developed to realize full color. For VR applications, large and high-resolution displays are required, so technologies have been developed to implement a small pixel size by using the TFT process. For small-form-factor AR devices, a small device is required, so technologies have been developed with a high pixel density, high luminance, a high frame rate, a large FoV, a small form factor, and low power consumption.

Although the performance of OLED microdisplays has improved, some technological obstacles should be overcome to broaden their fields of application and to increase their competitiveness over other microdisplays. First, the luminance of OLED microdisplays should be enhanced. Most optical systems in AR/VR glasses are inefficient. Especially, optical systems based on diffractive optical elements and holographic optical elements have low efficiency even though they have a small form factor and high transparency. As high luminance is essential for AR/VR glasses, the efficiency of OLED microdisplays should be improved by using an advanced device structure, a light extraction layer, direct patterning, and

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Table 1. Summary of the OLED microdisplays and their characteristics.

| Color    | Year | Size (inch) | Resolution | Pixel pitch (μm) | Pixel density (ppi) | Luminance (cd/m²) | Contrast ratio | Current efficiency (cd/A) | Max. frame rate (Hz) | Power (mW) | Reference |
|----------|------|-------------|------------|------------------|--------------------|-------------------|---------------|--------------------------|----------------------|------------|-----------|
| Mono-chromic | 2001 | 0.77 | 1,280 × 1,024 | 12 | ~ 2,100 | 600 | 100:1 | 85 | 920 | [61] |
|           | 2009 | 0.6   | 320 × 240 | 39 | ~ 650 | 5,000 | 400 | 100 | [54] |
|           | 2011 | 0.57 | 320 × 240 | 36 | ~ 700 | 24,000 | 3,000:1 | 400 | 100 | [55, 56] |
|           | 2012 | 0.61 | 2,600 × 2,088 | 4.7 | ~ 5,400 | 5,000 | 100,000:1 | 60 | 250 | [62] |
|           | 2017 | 0.19 | 304 × 256 | 12 | ~ 2,100 | 500 | 45.8 | 25 | 10–40 | [59, 60] |
|           | 2018 | 0.7   | 1,280 × 1,024 | 11.8 | ~ 2,300 | 460 | 2.8 | 90 | [23] |
| White     | 2001 | 1,280 × 1,024 | 12 | | 1,280 × 1,024 | 12 | ~ 2,300 | 974 | 4.87 | 400 | [11] |
|           | 2002 | 852 × 600 | 15 | ~ 1,700 | 200 | > 100:1 | 3.5–4 | 220 | [63] |
|           | 2006 | 0.19 | 320 × 240 | 12 | ~ 2,300 | 100 | 120 | [64] |
|           | 2011 | 0.6   | 1,024 × 768 | 12 | ~ 2,100 | 235 | 19.5 | [65] |
|           | 2019 | 1.06 | 1,920 × 1,200 | 11.2 | ~ 2,250 | 10,000 | 8 | [52] |
|           | 2017 | 0.7   | 1,280 × 1,024 | 10.8 | ~ 2,300 | 1,000 | 28 | [33] |
|           | 2020 | 0.8   | 1,920 × 540 | 10.2 | ~ 2,490 | 1,000 | 19.5 | 60 | [51] |
| Two-color | 2018 | 1,400 × 1,400 | 20 | 1,250 | 85 | [28] |
| Full-color | 2006 | 0.28 | 320 × 240 | 18 | 1,428 | 100 | 60 | 15 | [66] |
|           | 2009 | 0.77 | 1,280 × 1,024 | 12 | 2,300 | 310 | > 60,000:1 | [67] |
|           | 2012 | 0.61 | 1,280 × 1,024 | 9.4 | ~ 2,700 | 250 | 100,000:1 | 60 | 250 | [62] |
|           | 2014 | 0.23 | 640 × 400 | 7.8 | ~ 3,200 | 1,000 | 10,000:1 | 80 | [68] |
|           | 2014 | 0.39 | 1,028 × 768 | 7.8 | ~ 3,200 | 500 | 10,000:1 | 180 | [68] |
|           | 2014 | 0.7   | 1,920 × 1,080 | 8.1 | 3,147 | 200 | 100,000:1 | [68] |
|           | 2015 | 0.6   | 800 × 600 | 16 | ~ 1,580 | 75 | 350 | [56] |
|           | 2016 | 0.6   | 800 × 600 | 16 | ~ 1,580 | 75 | 350 | [56] |
|           | 2017 | 0.86 | 1,920 × 1,200 | 9.6 | 2,645 | 2,000 | [26] |
|           | 2018 | 1.06 | 2,048 × 2,048 | 9.3 | ~ 2,700 | 5,000 | > 10,000:1 | 90 | [27] |
|           | 2018 | 4.3   | 3,840 × 4,800 | 17.6 | 1,443 | 150 | > 15,000:1 | 120 | [69] |
|           | 2018 | 1     | 1,920 × 1,200 | 11 | 2,300 | 300 | > 100,000:1 | 120 | 200 | [70] |
|           | 2018 | 0.5   | 1,600 × 1,200 | 6.3 | 4,032 | 2,000 | > 100,000:1 | 120 | 310 | [47] |
|           | 2018 | 2.17 | 3,600 × 3,240 | 11.4 | 2,228 | 120 | 200 | [45] |
|           | 2019 | 5.87 | 5,120 × 2,880 | 25.4 | 1,000 | 10,000 | 42 | [42] |
|           | 2019 | 0.64 | 1,280 × 720 | 11 | 2,300 | 300 | > 100,000:1 | 120 | 160 | [71] |
|           | 2019 | 0.39 | 1,920 × 1,080 | 4.5 | 5,644 | > 100,000:1 | 90 | [48] |
|           | 2019 | 0.23 | 640 × 360 | 7.8 | ~ 3,200 | 5,000 | > 10,000:1 | [38] |
|           | 2019 | 0.62 | 1,280 × 720 | 10.8 | 2,351 | 180 | 150 | [46] |
|           | 2019 | 0.28 | 1,280 × 720 | 4.5 | 5,291 | 180 | 150 | [46] |
|           | 2020 | 3.23 | 2,160 × 2,400 | 9.0 | 245 | [43] |
|           | 2020 | 1,920 × 1,200 | 11 | 2,300 | 10,000 | 20 | 60 | 245 | [35] |
|           | 2020 | 0.59 | 800 × 600 | 15 | 1,700 | 31–33 | [24] |
efficient materials. Second, the driving voltage of OLED microdisplays should be reduced. As the resolution of the display panel increases, the size of the transistor and the circuit line should be reduced to limit the driving voltage and the current. This is very significant particularly in the tandem structure. Finally, the pixel crosstalk, which can degrade the color purity of the display, should be eliminated. Due to the small subpixel pitch, the light from one subpixel can affect adjacent subpixels, which is called optical crosstalk. This can be decreased by reducing the distance between the EML and the CF. Electrical crosstalk, which means that the voltage of one subpixel affects adjacent subpixels, results in current leakage. Electrical doping to reduce the driving voltage can encourage electrical crosstalk. Consequently, the conductivity of the electrically doped common layer should be carefully controlled to prevent electrical pixel crosstalk. Through continuous efforts of many researchers to solve these problems, we believe that OLED microdisplays can be sufficiently applied not only to AR/VR devices but to various other devices.

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