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Highly transparent, ultra-thin flexible, full-color mini-LED display with indium–gallium–zinc oxide thin-film transistor substrate

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Abstract
Mini-LED and micro-LED are expected to be the next-generation display by virtue of their diverse applications. In this study, an 8-inch flexible mini-LED display was fabricated using an indium–gallium–zinc oxide (IGZO) thin-film transistor (TFT) backplane that adopted a top-gate structure, with a pixel pitch of 0.55 mm and a resolution of 320 x 160, 46 PPI. With colorless polyimide (CPI) as the substrate, the mini-LED panel has a thickness of less than 0.2 mm, and a transmittance is over 60%. The world's first 8-inch, full-color, flexible mini-LED with IGZO-TFT backplane is demonstrated.

KEYWORDS
active matrix, flexible, IGZO TFT, micro-LED, mini-LED, transparent

1 | INTRODUCTION

Recent years have witnessed a surging demand for myriad of applications, such as highly deformable, wearable, and portable devices, which have been received extensive attention. Accordingly, development and application of transparent display and flexible display technology became more integrated into products.[1–3]

Micro-LED and Mini-LED technologies are considered as the best solution for flexible display and transparent display. Different from LCDs, Micro-LED and Mini-LED are solid-state and self-emitting display, which is superior in terms of response time,contrast ratio, brightness, and ultra-thinness.[4–7] In addition, LEDs as individual emitting devices, LEDs could be large-scale assembled onto various substrates ranging from glass to rubber and plastic.[8,9] Generally, LEDs are used for backlight in common LCD modules, in which most of the light is absorbed by polarizers, liquid crystal layers, and color filter and only 5%–10% of the light emitted by LED backlight can be used, thus causing high power consumption.[10–12] However, the structure of self-emitting display in LEDs facilitates the transparence of display without polarizer and color filter. Also, Micro-LED and Mini-LED outperform organic LEDs (OLEDs) on the ground of their longer lifetime and superior stability. Despite significant progress over the past decades in OLEDs, flexible OLEDs have been studied with the feasibility of flexible display.[13,14] However, the application of OLEDs is still limited in terms of their low efficiency, short life time, and low brightness. In view of this, an ultra-barrier coating is indispensable to reduce the performance degradation of OLEDs.[15,16] In contrast, LED requires minimal encapsulation on account of its inorganic semiconductor-emitting layer. In view of these reasons, Micro-LED and Mini-LED as promising technology have attracted significant interest in flexible and transparent display applications in terms of wearable devices, curved automotive and some new-tech display.

In recent years, tens of companies and research institute have been involved in mini-LED and micro-LED technology worldwide. Samsung demonstrated its first

146-inch full-color micro-LED display, called “The Wall” in 2017, featuring more than 960 × 540 micro-LEDs with the pixel pitch 0.84 mm in one module.[17,18] In comparison with LCD displays, “The Wall” is equipped with higher picture contrast (10,000:1), wider viewing angle of 155°, higher color purity and wider color range.[19]

In some other studies, reporters have presented the possibility of using flexible inorganic LEDs on a plastic substrate. In 2012, Hyeon Gyun Yoo et al. using standard soft lithography technology transferred 2 × 2 GaN blue LED arrays onto flexible polyimide (PI) substrates. In this study, the bending radius of the flexible GaN LED is up to 3.5 mm without significant change in electrical property.[20] However, the present fabrication is only applied to flexible Back Light Unit (BLU) devices, without brightness adjustment. In 2019 SID display, Playnitride exhibited a 7.65 inch full-color transparent Micro-LED with LTPS glass backplane - a transparency of 60 percent, which had attacted numerous vistors. But the to our knowledge, the number of direct display application of mini-LED or micro-LED with flexibility and transparence is relatively few.

The active matrix (AM) mini-LEDs full-color display based on a glass substrate in our previous work was demonstrated that active matrix thin film transistor has a promising application for large-size display.[21] Based on some researchs of flexible display technloy, utilized the glass substrate coated and cured and cured colorless PI substrate and laser lift off (LLO) process could be a candidate for flexible substrate.[20,22-24]

In this study, an 8-inch flexible full-color mini-LED display was fabricated in combination red, green, and blue (RGB) mini-LED. The display adopted the colorless polyimide (CPI) as substrate, driven by active matrix (AM) indium–gallium–zinc oxide (IGZO) thin-film transistor (TFT). After that, the display panel was fixed in a structural component, and the radius of curvature equals 100 mm. Cooperated with CPI as substrate, the thickness of the mini-LED panel is less than 0.2 mm, and the transmittance rate is over 60%. Owing to the AM IGZO TFT driving technology, the mini-LED display bestowed with inherent color quality and better motion reproduction. Finally, the world's first 8-inch, full-color, flexible mini-LED with IGZO-TFT backplane is demonstrated.

2 | PIXEL DESIGN

As illustrated in Figure 1, the pixel pitch of the flexible display mini-LED is 550 μm with RGB subpixels incorporated inside. The size of all these three color mini-LEDs is 100 × 200 μm. The mini-LEDs are located at the bottom part of the pixel. Flip chips were selected as spontaneous emission devices. Two bonding pads of panel were

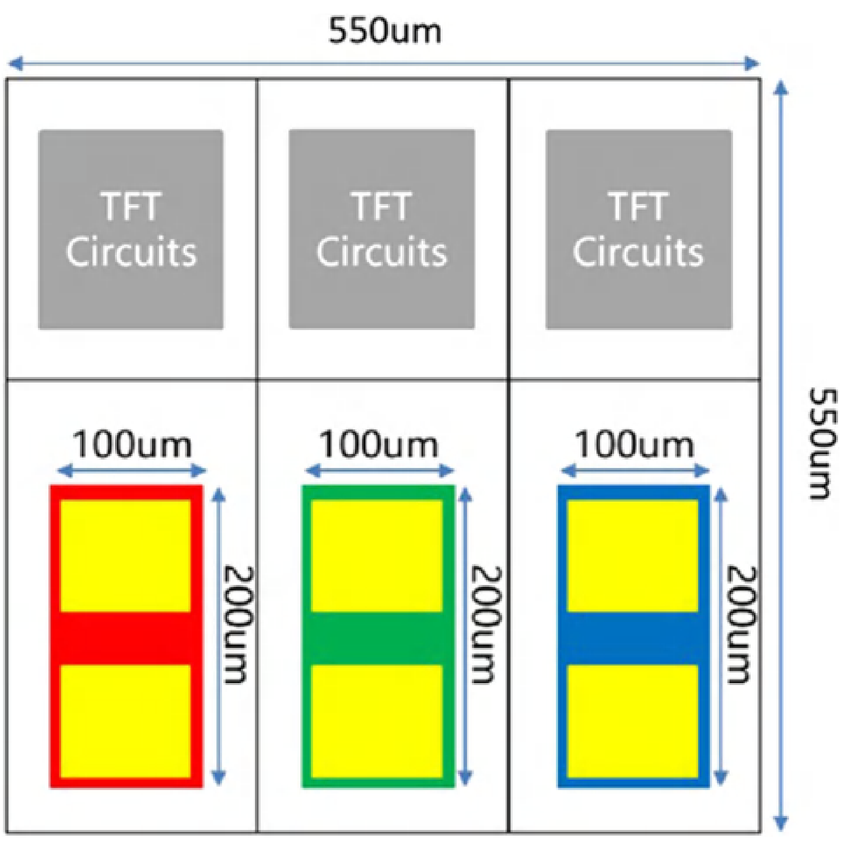

FIGURE 1 Schematic of pixel design

exposed for each mini-LED at the bottom of subpixel and above the mini-LEDs, the TFT of circuits were designed for different color LEDs, respectively.

As a spontaneous device, the small size of mini-LED facilitates the pixel design and transparence of display but the proportion of the light-emitting area is only 21%. To further enhance the transmittance, we propose three methods to improve the transparency of the backplane. The first one, suggested in order to reduce the TFT size, is the adoption of a top-gate structure TFT in this pixel design, which has a miniumu area in theory due to its self-aligned process. Secondly, a transparent connecting elecrode material-ITO (indium tin oxide) can be used in the structure, instead of conventional metallic wire.[25-27] Ensure that the solder paste could be printed on the connecting electrode, a metal electrodes was deposited on the top of ITO, as shown in Figure 3, for the purpose of making the connecting electrodes small enough to position them vertically under the Mini LED. The ITO layer, in this case, serves as wire expanding from TFT circuits, which connect with LED connecting electrode through the opening holes. At last, a high aperture ratio of pixel was achieved - about 82% by calculation. The third method to boost the transparence is reducing the absorbance of substrate. Recently, flexible substrate made of plastics (e.g. polyimide (PI)) instead of glass has been used in the display industry, but the problem lies in that most of existing flexible display technology, for example OLED, utilizes yellow polyimide (YPI) as TFT substrate, by reason of high glass transition temperature (Tg), good mechanical properties and low coefficient of thermal expansion (CTE). In this study, in order to meet the demand of transparent application, colorless polyimide (CPI) is suitable to use as TFT fabrication substrate for the reason that it not only remains the merits of high transition temperature by also reserves the low CTE properties like YPI. Eventually, on the premise of ensuring realized flexible display, the transparency of pixel was expected to be improved through the design of TFT circuits and the selection of materials as much as possible.

3 | PROCESS FLOW

The flexible display was fabricated as shown in the process below, in Figure 2A-F. In the first step, TFT was formed on the glass substrate coated and cured CPI (Figure 2A). Mitsubishi Gas Chemical Company provided the CPI and the thickness of colorless PI is 10 μm. A buffer layer (SiN/SiO) was deposited on the CPI, which acted as a flattened layer and protective layer during TFT process for CPI. Later on, the top gate IGZO TFT arrays were developed on the CPI substrate at Gen 4.5.

The IGZO TFT has advantages in terms of electron mobility and low-temperature fabrication process, which are considered to be suitable for large-screen display and flexible display.[28,29] Moreover, the patterned IGZO TFT has a distinct advantage: it could be fabricated at low temperatures. The cross-section of IGZO TFT structure on backplane is shown in Figure 3. The second step, shown in Figure 2B, is done after the manufacturing process of TFT. The flip chips were

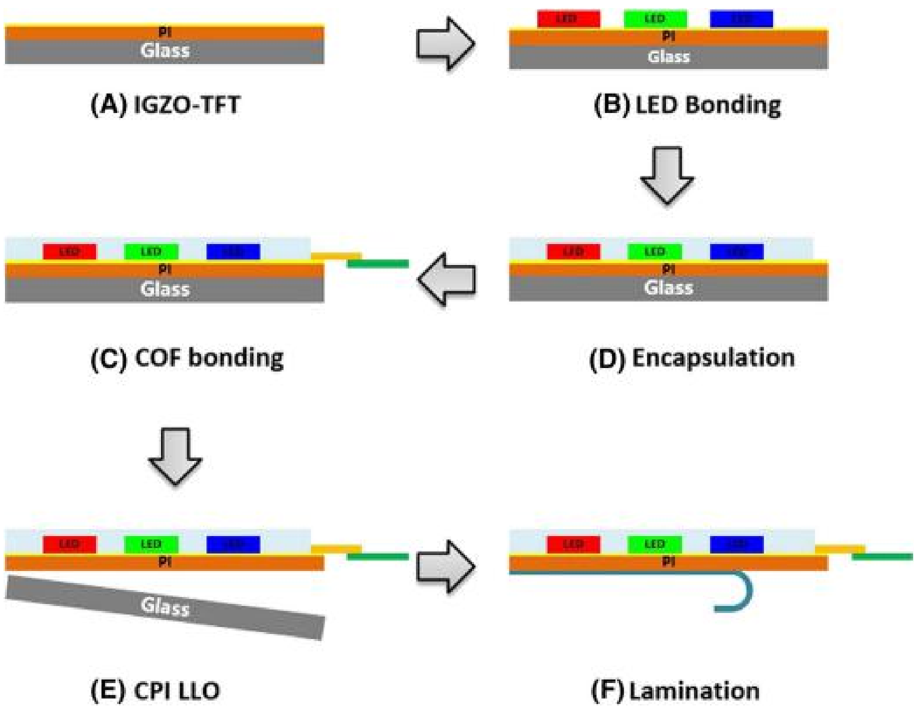

FIGURE 2 The schematic diagram of flexible mini-LED manufacture process

TABLE 1 Flexible mini-LED display performance

AM mini-LED flexible display	
Items	Specification
Panel Size	8 inch
Resolution	320 × 160
Pixel Pitch	0.55 mm
Chip Size	100 μm × 200 μm
Active area	176 mm × 88 mm
TFT type	TGITGO
Transnittance	60%
Thickness	200 μm

Abbreviations: AM, active matrix; IGZO, indium–gallium–zinc oxide; NTSC, National Television Standards Committee; TFT, thin-film transistor.

bonded onto the backplane by solder paste proceed with transferred and aligned to the pattern of the substrate, forming an electrical connection in reflow soldering process. After that, the third step (Figure 2C) is to encapsulate the panel by silicone. The silicone layer serves not only an encapsulation of the panel, but also a protection of the layer for CPI during the LLO process. CPI film is fragile and easy to curl, differently than the yellow polyimide (YPI).[30] So encapsulation layer should maintain thick enough to neutralize the internal stress of CPI. The 200 um silicone layer was created by adjusting the hardness, Young's modulus, and coating method of silicone.

The forth step, shown in Figure 2D, is the CPI LLO process. It is noteworthy that the process of Chip On Film (COF) and driving IC bonding to panel was proceeded before the CPI laser lift off (LLO) procedure, as an intention to reduce the risk during the process engineering. The LLO is used for stripping CPI from the carrier glass and it was assisted by Han's Laser Technology Industry Group Co. The wavelength of the laser is 308nm, which is in the UV wave length range. The polyethylene glycol terephthalate (PET) lamination (Figure 2E) is the last step of the process, when a barrier PET film was laminated on the back of CPI substrate, with a function to protect the surface from moisture and keeping device stable.

4 | RESULT AND DISCUSSION

Thanks to the integration of mini-LEDs and IGZO TFT backplane with flexibility and transparency characteristics, the proposed flexible and transparent mini-LED direct display can be successfully created. It is demonstrated in Figure 9, an 8-inch flexible and transparent mini-LEDs display with 100 mm in radius of curvature, with a pixel pitch of 550um. The panel also has a pixel circuit of 320 x 160 pixels, which equals to 59 PPI. The RGB mini-LEDs are all flip chip structure with a size of 100 × 200 μm. Some of the specifications of the flexible mini-LED display are listed in Table 1.

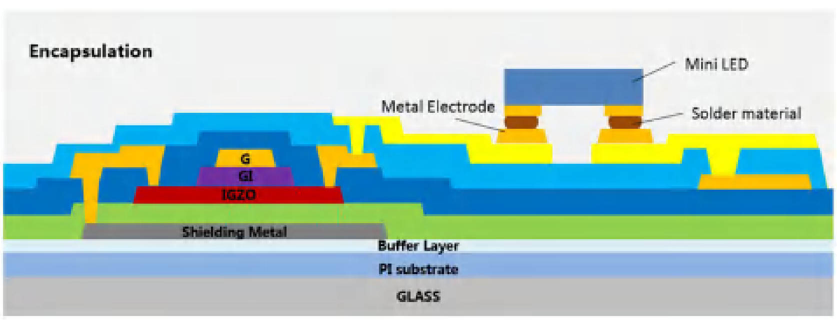

FIGURE 3 The TFT structure of panel

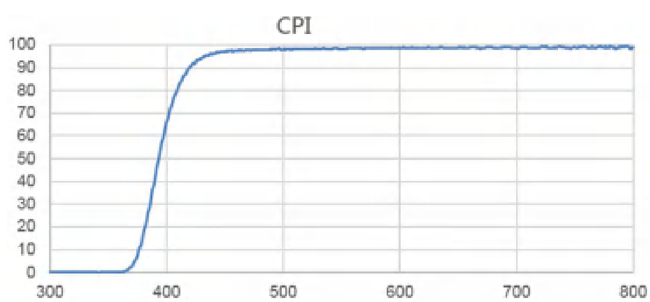

FIGURE 4 Transmittance spectra of CPI

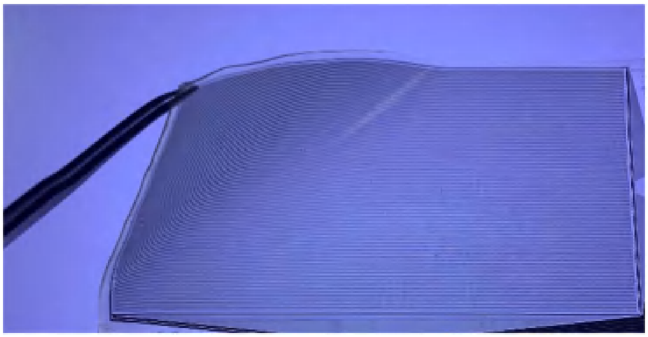

FIGURE 5 The manual bending active matrix (AM) mini-LED was placed on the backlight

To complete this experiment, we measured the optical performance of the fabricated mini-LED display. In Figure 5, an 8-inch panel with bonding mini-LEDs was placed on the backlight with yttrium aluminum garnet (YAG) phosphor LED light source and it is obviously to discern the white light through the backlight. Simultaneously, the CPI substrate exhibits a promising flexibility and transparency. As shown in Figure 4, an optical transmittance of CPI film is observed over ~95% during visible wavelength range of the spectrum. Meanwhile, in order to improve the transparency of TFT backplane, transparent conductive layer was adopted as panel's pad for bonding LEDs-this one would be fabricated metal electrode on it. As a result, the transmittance rate of full-color mini-LED display was over 60%.

In previous research, the common RGB pixel was replaced by RGBW pixel arrangement or by coating a thinner color filter layer during the fabrication process, in hope of improving the transmittance of LCD screen. Nonetheless, such an operation could result in the color gamut value being sacrificed. Moreover, on account of the necessity of the polarizer, the improvement of light transmittance is limited in LCD technology. Recently, AMOLED is regarded as a new candidate for transparent display due to self-luminous and high color gamut. Fine Metal Mask (FMM) patterned technology was adopted to make cathodes but has been suffering from irrecoverable deformation under high-temperature evaporation process. It is arduous for OLED to take into account both transparency and flexibility, due to the fact that it requires the use of elaborate encapsulation. On the other hand, in Mini LEDs technology, the structure of display is extremely simple, entailing no complicated structure (without CF and polarizer) or rigorous encapsulation. Furthermore, it could combine such outstanding features as transparency, flexibility and color gamut, in one display device. What makes it more extraordinarily is that the thickness of the whole device is only about 200 um, thus being more suitable for wearable device, curved automotive and other particular display applications.

For a flexible display, a wide viewing angel is indispensable and it is essential to ensure the images of screen should be seen at any angle.[31–33] However, LCD has long suffered from the narrow viewing-angle characteristics.[34] In this study, the brightness view angle of mini-LED display was measured before LLO process. The curves of view angle varies with the brightness were measured from −90° to 90° and shown in Figure 6. When the brightness drops of 50%, the viewing angle of RGB still remain at 124°, 155°, and 154°, respectively, which is significantly higher than LCD and OLED. Simultaneously, a mismatched angular distribution between red and blue/green Mini-LEDs happen. The view angles of blue and green Mini-LEDs are wider than the red ones. The main reason of this phenomenon is that the sidewall emission of a micro-scale LEDs between red and glue/green are different. The sidewall emission is related to the refractive index of materials and device structure.35

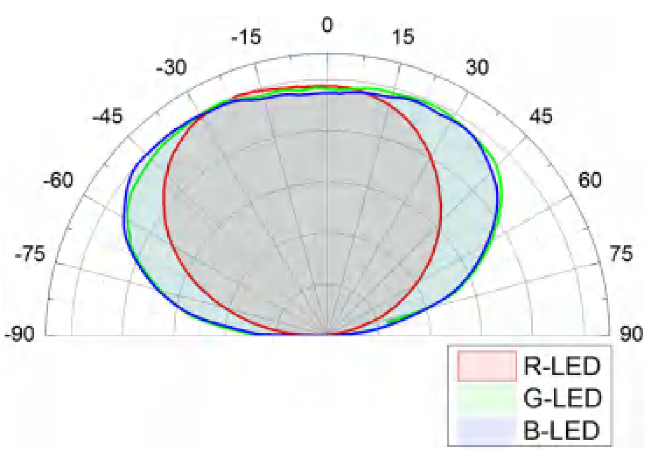

FIGURE 6 The viewing angle of red, green, and blue (RGB) mini-LEDs

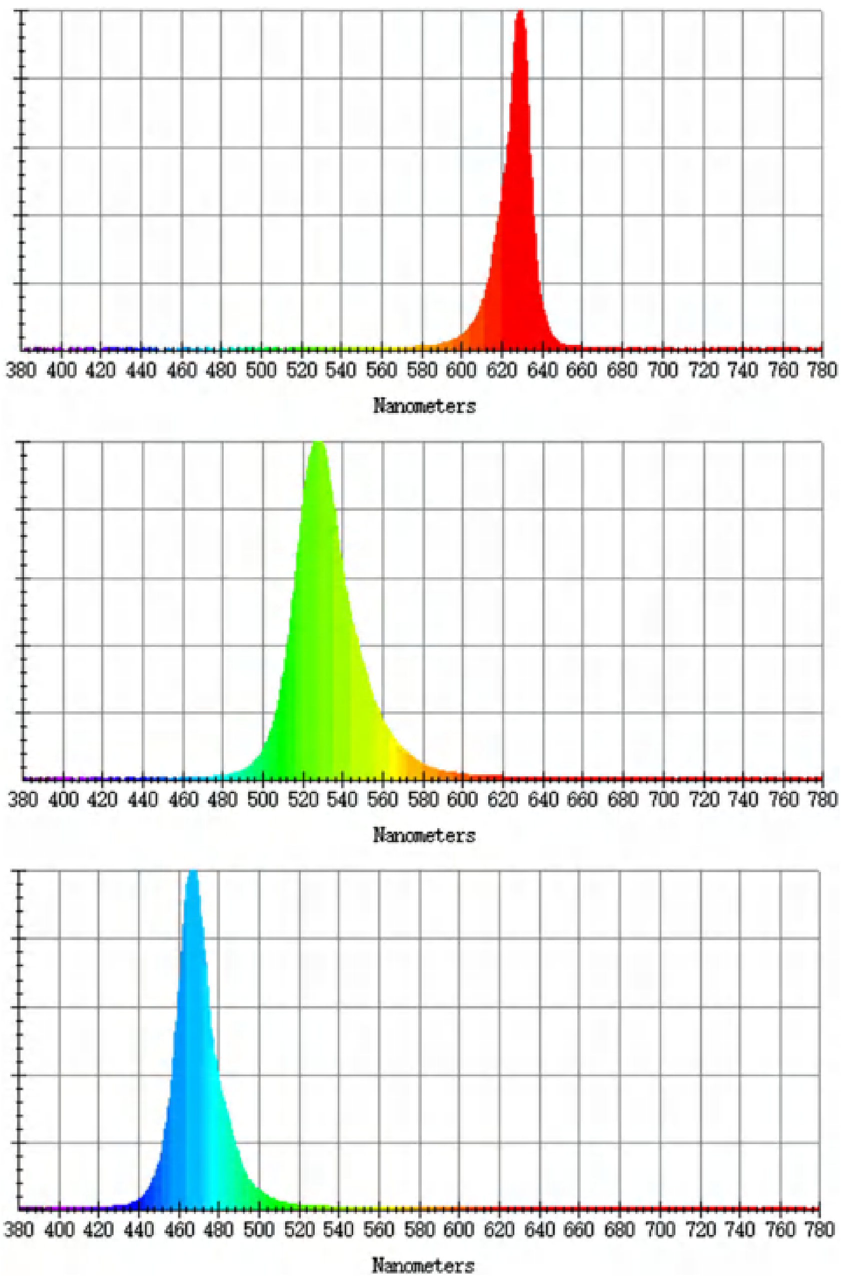

FIGURE 7 The spectrum of red, green, and blue (RGB) mini-LED

For this study, AlGaInP and GaN manufactured the red Mini-LED and blue/green Mini-LEDs. As a result, the Mini LEDs display has a mismatched angular distributions between red and glue/green Mini-LEDs. Although the Mini-LEDs display has mismatched angular distribution in RGB LEDs, compared with LCD and OLED display, it is much more suitable for high view angle display applications.

Moreover, we evaluated the spectra of the full-color flexible mini-LEDs. RGB LED chips on glass substrate were lighted up to measured, individually. As shown in Figure 7, the optical emission spectrum measurement results of RGB micro-LED showed peak wavelength of 620, 528, and 467 nm, respectively. The emission light also exhibits a narrow full width at half maximum (FWHM), which is all less than 30 nm. RGB emission with their respective corresponding Commission International de L'Eclairage (CIE) coordinates at (0.692, 0.307), (0.207, 0740), and (0.127, 0.069) were obtained from the mini-LED device, respectively. The combination RGB mini-LEDs with the AM IGZO TFT backplane realized a color gamut of a full-color mini-LED display is up to 114% National Television Standards Committee (NTSC), 118% of DCI-P3, and 85% of B.T. 2020 in CIE 1931 color space, and 120% of NTSC, 110% of DCI-P3, and 80% of B. T. 2020 in CIE 1976 color space, respectively. The color

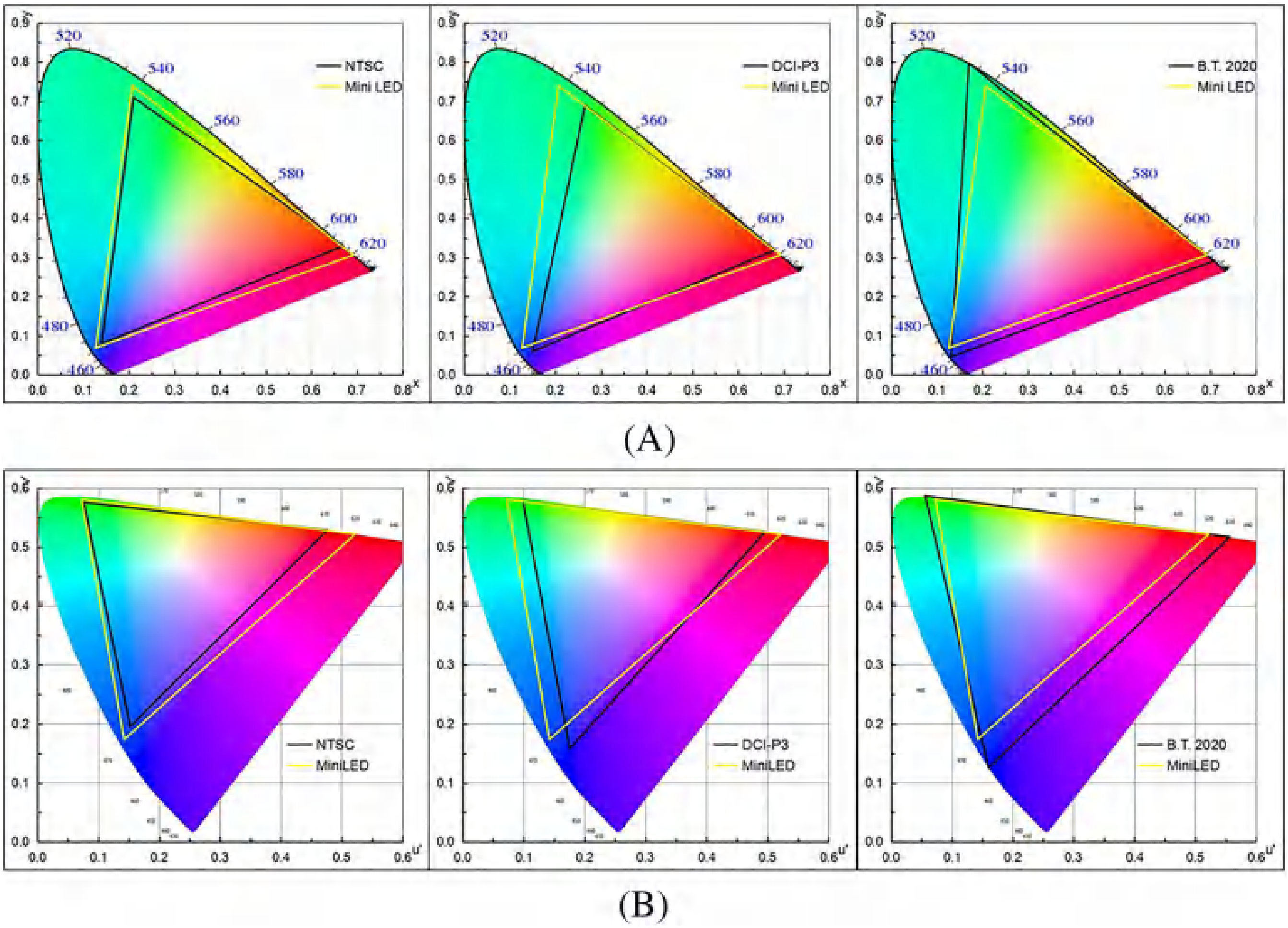

FIGURE 8 Color gamut of flexible active matrix-thin-film transistor (AM-TFT) mini-LED display in CIE 1931 (A) and CIE 1976 (B) color space

TABLE 2 RGB mini-LED spectrum information and the color gamut of mini-LED display

Item		WP (nm)	FWHM (nm)	x	y	u′	V′
R		629	12	0.692	0.307	0.521	0.521
G		528	27	0.207	0.740	0.072	0.581
B		467	17	0.127	0.069	0.143	0.174
Color Gamut (CIE 1931)	NTSC	114%					
	DCI-P3	118%					
	B.T. 2020	85%					
Color Gamut (CIE 1976)	NTSC	120%					
	DCI-P3	110%					
	B.T. 2020	80%					

Abbreviations: FWHM, full width at half maximum; NTSC, National Television Standards Committee; RGB, red, green, and blue.

coordinate of mini-LED in the CIE 1931 and CIE 1976 is demonstrated in Figure 8 and Table 2. In diagram shows that the coverage of mini-LED color gamut almost complete covers the NTSC. Figure 9 shows the appearance image of the flexible mini-LED display. This sample has been demonstrated in SID 2019 (Figure 9).

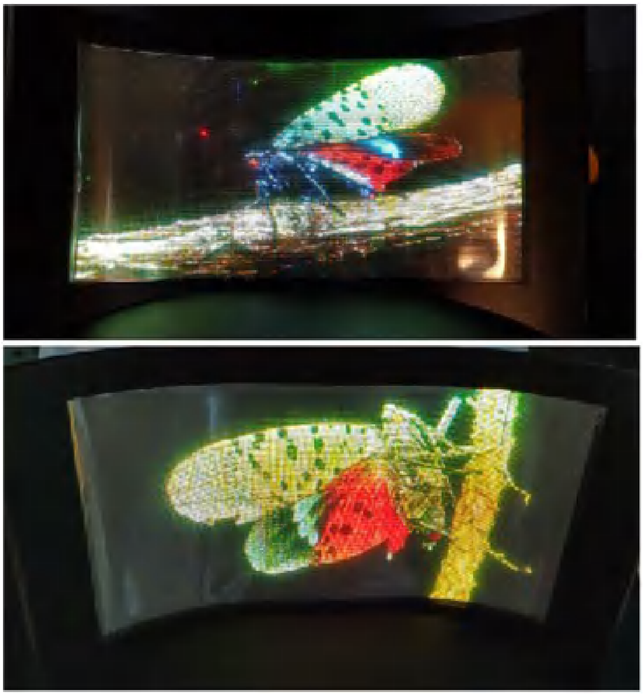

FIGURE 9 Eight-inch active matrix (AM) mini-LED display

5 | CONCLUSION

In summary, an 8-inch AM mini-LED display integraing both flexibility and transparency was demonstrated (Figure 9), driving by IGZO TFT backplane. In this work, by introducing novel pixel design, ITO wire, and small size LEDs, as well as high transparency CPI, we succeeded in fabricating an RGB mini-LEDs display with a transmittance of more than 60%, a pixel pitch of 0.55 mm and a resolution of 320x160. To realize flexibility of the backplane, PI LLO technology was utilized to separate CPI from glass backplane. All of these approaches resulted in color gamut of the display is up to 114% NTSC. This new mini-LEDs integration approach manifests merits including outstanding optical performance, high transparence, ultra slim, and flexibility.

It is the first time demonstration a self-emission device – Mini LEDs based on AM-TFT flexible backplane with a full-color transparent display. It is implied after this research that Mini-LED and Micro-LED have great and promising potential application in new-tech display, especially in flexible and transparent display realms. Moreover, we believe that it is a new feasible technology to realize a large-size micro-LED in display application.

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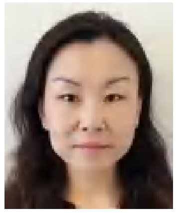

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