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3,000 ppi Full-Color "Silicon Display" with Monolithic Micro-LED and Color Conversion Technology

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ABSTRACT

3,000 ppi full-color "Silicon Display" has successfully been demonstrated based on monolithic micro-LED and Cd-free quantum dot (QD) color conversion technology. "Light-shielding wall (LSW)" is the key to prevent optical cross-talk. The demonstrator with 8.4um square pixel including RGB sub-pixels has shown wide color gamut exceeding 111% of sRGB.

1 INTRODUCTION

The market of augmented reality (AR) and mixed reality (MR) is beginning to emerge, and compact and highly-efficient near-to-eye display is strongly needed. [1] Although existing micro displays, such as LCOS and Micro OLED can be applied to the optical see-through AR/MR hardware, high-brightness micro-LED is by far the promising candidate for AR/MR gadget for the outdoor use.

While there have been many reports on monochrome micro-LED display devices [2,3], there have not been many reports on full-color devices. Recently, Professor Lau's team reported 423 ppi full-color micro-LED display with 60% color gamut of sRGB [4]. We have been working on the development of what we call "Silicon display" and have reported 1,000 ppi full-color and 3,000 ppi monochromatic devices. [5,6] Full-color micro-LED display with high pixel density is difficult to achieve due to the following two reasons. One is the low color conversion efficiency of QD materials, and the other is the color mixing of neighboring pixels caused by optical cross-talk.

In this paper, we report 3,000 ppi full-color Silicon Display for the first time. The demonstrator was shown to have wide color gamut exceeding 111% of sRGB. It should be noted that we used Cd-free QD material for this demonstrator. Cd-free QD complies with RoHS regulation, however, its performance is generally lower than Cd-containing QD. Therefore, we optimized the process to form QD layers. Also, we established the process to form fine LSW pattern for 3,000 ppi demonstrator in order to decrease the optical cross-talk between sub-pixels.

2 EXPERIMENT

Figure 1 shows the fabrication process of Silicon Display. InGaN/GaN blue LED arrays with micro-LED element (sub-pixel), each ca. 4.2 x 4.2 um in size, were formed on a sapphire substrate. LED wafer was diced into LED array chips. The LED array chip was then flipbonded onto driver LSI chip so that each micro-LED element could be driven by display driver. The sapphire substrate of micro-LED was then removed by laser-lift-off process. Finally, color conversion layers using Cd-free QD materials were formed on green and red sub-pixels. The cross section of one pixel of Silicon Display is schematically shown in Fig. 2. LSW was formed between each sub-pixels in order to prevent optical cross-talk. For color conversion from blue to red and green, Cd-free QD layer was formed on each red and green sub-pixel, respectively. Color filter was also formed onto the color converter in order to absorb the blue light passing through the color converter layer to obtain good chromaticity. The formation of color converter and the color filter was done by well-developed photolithography process.

The size of this 3,000 ppi Silicon Display was about 0.13 inch and the resolution was 352 x 198 pixels.

3 RESULTS

3.1 3,000 ppi Monochrome Micro-LED display

Figure 3 shows the photograph of blue monochrome micro-LED arrays prepared for 3,000 ppi full-color Silicon Display and representative monochrome image of 3,000 ppi Silicon Display. As shown in Fig. 3 (a), each pixel was 8.4um square and consists of RGB sub-pixels and common cathode. One common cathode works for 4 pixels including 12 sub-pixels. The brightness was measured to be over 30,000 cd/m^2 at driving current of 4 A/cm^2. The demonstrator shows excellent image quality as shown in Fig. 3(b).

3.2 3,000ppi Full-Color Silicon Display

3,000 ppi full-color Silicon Display was fabricated by forming LSW and Cd-free QD with color filter on monochromatic 3,000 ppi Silicon Display by using i-line stepper.

SEM image of Silicon Display after forming LSW and Cd-free QD color converter is shown in Fig.4 (a), and the light emission images of single pixel for each color are shown in Fig.4 (b), (c), and (d). It can be seen from Fig.4 (a) that LSW and Cd-free QD color converter were finely patterned on each sub-pixel with ca. 4.2 x 4.2um in size. Care was taken not to cause local color imbalance in the subpixel color arrangement. Good color purity was confirmed as can be seen in Fig.4 (b), (c) and (d), but there was small optical cross-talk in the current demonstrator. The color coordination and the area ratio of obtained color gamut to typical color spaces were summarized in Table 1. The area ratio to sRGB color space was measured to be about 111% as shown in Fig.5.

4 DISCUSSION

We have demonstrated that 3,000 ppi Silicon Display with Cd-free QD color converter shows very good color gamut and that LSW is the key to reduce the optical cross-talk between sub-pixels. The color gamut of 3,000 and 1,000 ppi Silicon Display was 111% and 120% of sRGB [5,6,7], respectively. Smaller color gamut of 3,000 ppi Silicon Display is due to the small cross-talk which can be solved by further optimizing the structure and the process.

For the near-to-eye display, brightness of more than 5,000 cd/m^2 and the resolution of more than 3,000 ppi are required especially in the outdoor use. The brightness of the blue monochromatic Silicon Display was over 30,000 cd/m^2, so we strongly believe that Silicon Display has enough potential for the AR/MR devices for outdoor use. [7]

5 CONCLUSIONS

We demonstrated 3,000 ppi full-color Silicon Display based on monolithic micro-LED technology for the first time. There are two key improvements in color conversion technology: 1) fine patterning of Cd-free QD and LSW to 3,000 ppi by using i-line stepper and 2) color conversion with Cd-free QD material. Silicon Display can comply with RoHS regulation and meet demand for high pixel density to realize compact AR/MR gadgets.

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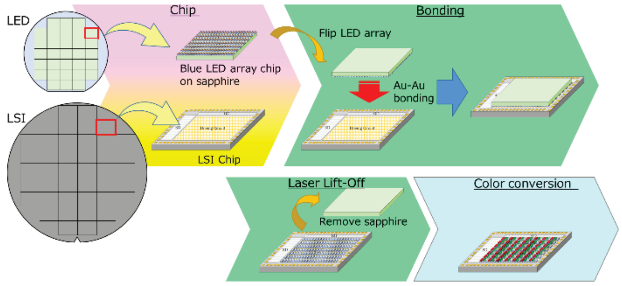

Fig. 1 Process Flow of Silicon Display

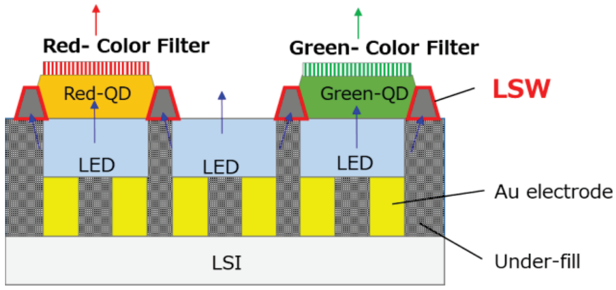

Fig. 2 Cross section of one pixel of Silicon Display

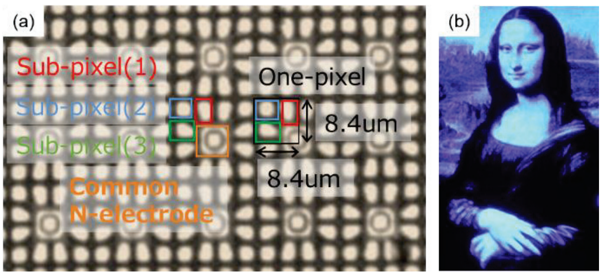

Fig. 3 Blue Monochrome 3,000 ppi Silicon Display: (a) photograph of micro-LED array and (b) representative monochrome image

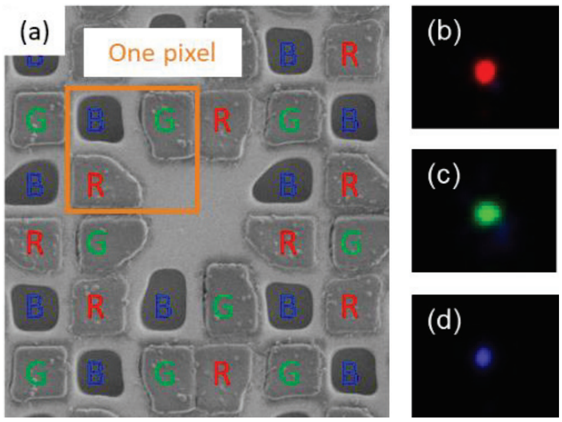

Fig. 4 Full-Color 3,000ppi Silicon Display : (a)SEM image after forming LSW and Cd-free QD color converter, (b)(c)(d) the light emission image of single pixel for each color.

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Table 1 Color coordination of 3,000 ppi full-color Silicon Display and its area ratio to typical color spaces

Color coordination			Area ratio		
	x	y	BT2020	NTSC	sRGB
R	0.596	0.272	59%	78%	111%
G	0.233	0.634			
B	0.152	0.031			

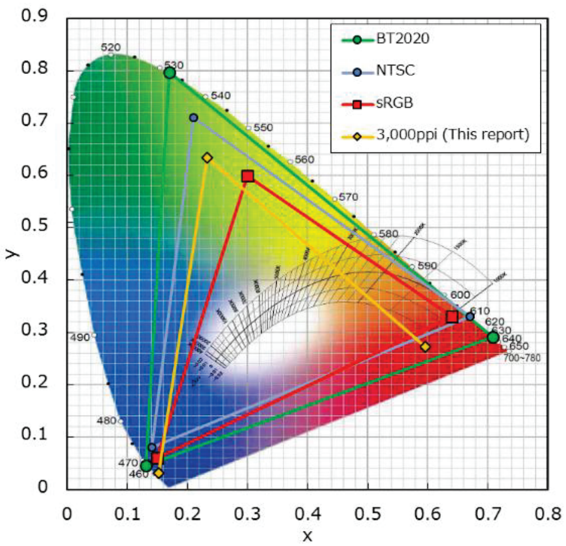

Fig. 5 Chromaticity diagram