High-Resolution (1,000 to over 3,000ppi) Full-Colour "Silicon Display" for Augmented and Mixed Reality

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ABSTRACT

We present the status of III-nitride micro-LED display bonded onto silicon backplane. 0.38-inch full-colour display with a resolution of 1,053 ppi has been successfully demonstrated. Progress toward higher resolution is also described. We believe our "Silicon Display" is ideally suited for near-to-eye displays for augmented and mixed reality.

1 INTRODUCTION

Micro-LEDs have been attracting a lot of attention recently since they are one of the strong candidates for enabling near-to-eye microdisplays for applications in augmented reality (AR) and virtual reality (VR) [1]. Near-to-eye displays are attached in close proximity to human eyes and need to be very small if we consider eye-glass type display system. Resolution needs to be very high for near-to-eye configuration, and also high brightness is a strong requirement especially in the case of AR and mixed reality (MR) devices, since they are often used outside in the sun.

Micro-LEDs with size around 10 μm or less can exhibit very high efficiency [2] and their brightness is expected to be much higher than that of other counterparts, such as micro-OLEDs. Also LED epiwafers can be processed into very small pitch monolithic arrays using well-established process technologies. Those arrays have already been reported with both high brightness in the range of 100,000 nits and high resolution of 5,000 ppi [3].

Micro-LED displays with full-colour RGB sub-pixels of 35x35 μm size have also been reported using quantum dot (QD) as colour converter deposited by inkjet printing [4, 5]. However, this sub-pixel size is still too large for AR and MR devices.

In this paper, we report 1,053 ppi full-colour micro-LED display, which we call "Silicon Display" [6], based on three key technologies: 1) monolithic micro-LED array, 2) colour conversion layer formed with photo-lithography process, and 3) light shielding walls (LSWs) to prevent optical cross talk [8]. Micro-LED arrays with colour converter are bonded onto silicon backplane to form driver-integrated full-colour micro-LED arrays. We confirmed that this Silicon Display has wide colour gamut exceeding 120% of sRGB. We also present our progress toward display resolution higher than 3000 ppi.

2 EXPERIMENT

2.1 Process flow of Silicon Display

Figure 1 shows the fabrication process of Silicon Display. InGaN/GaN semiconductor based blue LED arrays with micro-LED element (sub-pixel), each 8x24 μm in size, were formed on a sapphire substrate. LED wafer was then diced into micro-LED array chips. The LED array chips were then bonded in flip-chip configuration onto the silicon large scale integration (LSI) driver chip so that each micro-LED element is individually addressable. Sapphire substrate was then removed using standard laser lift-off process. Finally, colour conversion layers using QD materials were formed to obtain green and red emitting micro-LED sub-pixels using photolithography process.

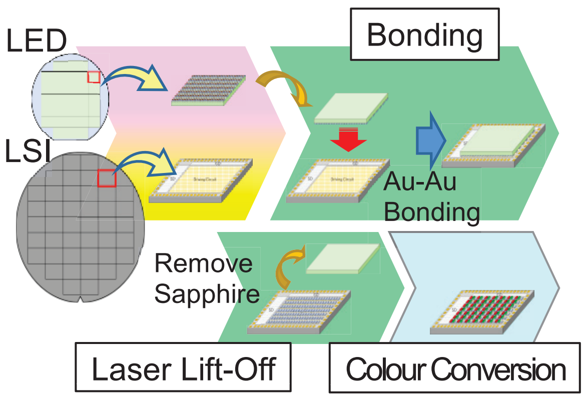

Fig.1 Process Flow of Silicon Display

2.2 Colour conversion

Figure 2 shows the schematic of one pixel of Silicon Display. Red and Green sub-pixels were formed by converting light from blue LED using QD colour converter. QD materials were mixed into photo-resist before being deposited onto the sub-pixel surface by photolithography process to form a QD colour converter layer. Due to the sub-micron size of the QD particles they are suitable for processing onto Silicon Display with sub-pixel size smaller than 10μm.

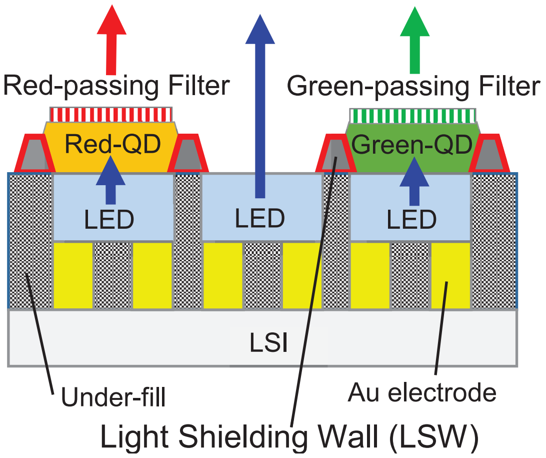

Fig. 2 Schematic diagram of a pixel of Silicon Display

In the current pixel configuration (QD conversion efficiency and layer thickness), Blue light emitted from each sub pixel is not completely absorbed by the QD layer and this leads to the degradation of the colour purity of Silicon Display. Therefore colour filters were formed on the QD colour converter layer to reduce the amount of blue light passing through and improve the red and green colour coordinates.

Further optimisation of the display structure have been implemented in Silicon Display: firstly light emission from QD colour converter is isotropic. Light shielding walls (LSWs) were formed between each sub-pixels to prevent optical cross-talk. LSWs absorb light coming from the neighbouring sub-pixels and colour conversion layer. Secondly there is also light which is extracted from the sidewalls of the micro-LEDs themselves which can increase the cross talk between sub-pixels. To suppress this, an underfill resin with carbon black is spread between each micro-LED sub-pixels.

2.3 Micro-LED driver LSI

A driver LSI was designed so that each driver circuit could drive each sub-pixel LED in 8 bits, leading to 24-bit full-colour image. A bump bonding process was used to electrically and physically contact the micro-LEDs and driver chip. Silicon Display was then packaged as shown in Fig.3.

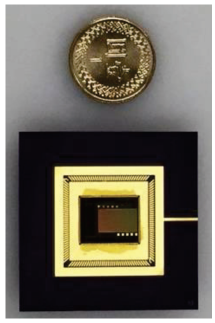

Fig.3 Photograph of Silicon Display in a ceramic package

3 RESULTS and DICUSSION

3.1 Performance of 1,053 ppi full-colour Silicon Display

A 0.38 inch RGB Silicon Display was achieved with a resolution of 1,053 ppi with 352x198 pixels. Each pixel was 24μm square and composed of RGB sub-pixels.

Silicon Display was programmed with peripheral driving board to show images and animations. Representative full-colour image of Silicon Display is shown in Fig.4 after optimising the gamma values. It was also shown that Silicon Display could be used for moving images as designed.

Fig.4 Representative full-colour image of 0.38 inch Silicon Display with a resolution of 1,053 ppi

Figure 5 shows the colour gamut of Silicon Display in CIE1931 colour diagram with and without LSWs.

The colour gamut of Silicon Display was significantly improved by the introduction of LSWs as shown in Fig.5. Table 1 reports the colour coordinates and display colour gamut. The colour gamut was measured to be over 120% of sRGB, which is sufficient for this type of display.

3.2 Higher resolution Silicon Display

We continue development toward higher resolution Silicon Display needed for near-to-eye microdisplays. Figure 6 shows the photograph of micro-LED arrays prepared for 3,000ppi full-colour Silicon Display. Each pixel was 8.4μm square with RGB sub-pixels.

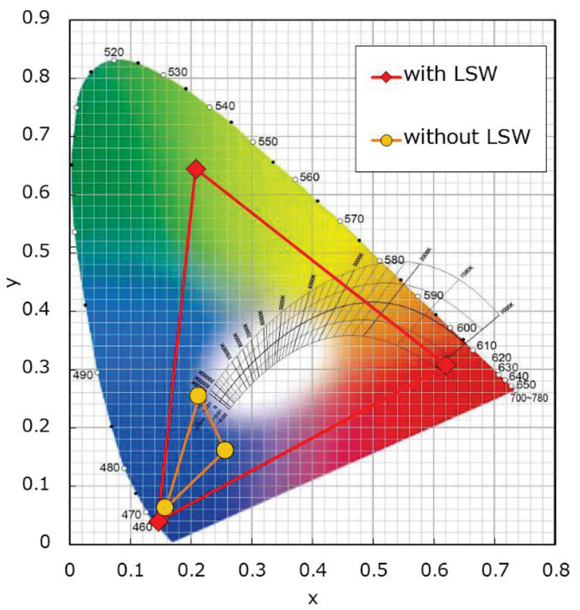

Fig.5 Colour gamut of Silicon Display in CIE1931

Table 1 Colour coordinates and colour gamut of Silicon Display with and without LSW

Structure	Colour coordinates			Colour Gamut		
		x	y	BT2020	NTSC	sRGB
Without LSW	R	0.257	0.162	3.2%	4.3%	6.0%
	G	0.213	0.255			
	B	0.158	0.063			
With LSW	R	0.620	0.308	63.7%	85.3%	120.5%
	G	0.208	0.645			
	B	0.146	0.040			

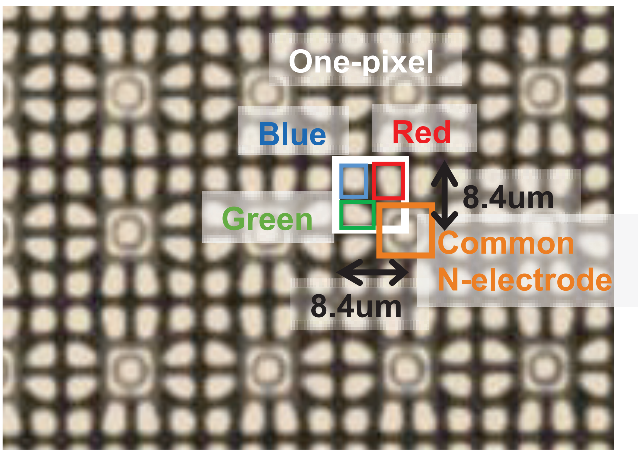

Fig.6 Photograph of 3,000 ppi micro-LEDs for Silicon Display

Colour conversion material has not been implemented yet. Representative monochrome images of 3000 ppi Silicon Display are shown in Fig.7. The number of pixels was the same with our 1,053 ppi Silicon Display. (i.e. 352x198) and the display size was 0.13 inch.

Fig.7 Representative blue monochrome image of 1.3 inch Silicon Display with a resolution of 3,000 ppi

4 CONCLUSION

We demonstrated 1,053 ppi full-colour Silicon Display based on micro-LED technology. Silicon Display has been fabricated with monolithic micro-LED array, colour conversion layer formed by photolithography, and light shielding walls to prevent optical cross talk. The colour gamut was shown to be over 120% of sRGB.

We have also fabricated 3,000 ppi Silicon Display, and confirmed that 3,000 ppi images in blue monochrome can be displayed.

These results demonstrated the suitability of Silicon Display for near-to-eye display in AR and MR applications.

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