A Fine-pitched Full-color Micro-LED Technology for AR/MR Displays

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Keywords: micro LEDs, colloidal quantum dots, micro-LED array, augmented reality, mixed reality

ABSTRACT

We demonstrate our recent study of a 0.55 inch full-color micro-LED display with 992 PPI resolution. The display is structured with a blue micro-LED array of 1984 PPI which was bonded on a CMOS driving matrix, and it is converted from the monochrome display to full colored one by colloidal quantum dots. The details of structure design and process are described in this article. The fine-pitched full-colored micro-LED display shows great potential in AR/MR reality in the near future.

1 Introduction

Augmented reality (AR) and mixed reality (MR) attract people's attention as important development for display in the next generation. They bring the benefits of hand-free operation, space-saving module size and they are able to mix the virtual information with real surrounding. However, these devices still have many technical obstacles, for example, the weight, the compactness, the optical performance, and the power consumption, etc., that need to be overcome [1].

Recently, micro-LED display has been regarded as a promising near-eye micro-display candidate for AR/MR applications due to its high resolution and high brightness [2]. Brightness defines the clearness of virtual images that can be seen in real surrounding environment, and the clearness can also be determined by the transparency and contrast properties of the AR/MR glasses. Due to the limitation of brightness, most current AR glasses are more suitable for indoor usage. Furthermore, many of them turn to reduce the transparency to lower the environment light for the better contrast and clarity. Micro-LED displays nowadays have the highest brightness compared to other technologies in the fine-pitch scale. Suitable screen color and brightness are possible for micro-LED based display even under outdoor daylight environment. With the high brightness performance, micro-LED display has advantages to become the next generation display of AR/MR device, and bring the benefit to outdoor application, transparency and contrast.

Although micro-LED displays show high performance, the technology of turning monochromic LED arrays to full colored LED arrays still remain a challenge. The mass transfer method [3] which transfer blue, green and red micro-LED from each original wafer to a different substrate become harder as the LEDs' size shrink to under 10 μm, especially for those of mechanical method like regular vacuum pick-up. Also, the current micro-LED devices show the degradation of quantum efficiency as the device size shrunk down to 10 μm due to various reasons such as the strong surface recombination and fabrication difficulties [4]. To overcome these difficulties, color conversion method [5], [6] is thus considered. In this method, the micro LED array is single-colored (usually blue) and the extra color conversion layer is applied to absorb blue photons and transfer them to red and green ones accordingly. This process of conversion can be achieved by blue photon absorption and subsequent radiative recombination in the color conversion layer. With high quantum efficiency available in the novel color conversion material, such as colloidal quantum dots, a good performance of this technology is expected.

In this paper, we introduce our recent result of a 992 ppi full-colored micro-LED display using color conversion method from our lab. A blue micro-LED array with 1984 ppi was first fabricated and followed with an integration of a color conversion layer. Color conversion layer (CCL) was patterned with colloidal quantum dots that can transform light from a shorter wavelength to a longer wavelength. Therefore, blue light LEDs can pump these quantum dots and emit red or green light. The optical properties of this color-converted micro-LED display were measured and show a wide color gamut exceeding 140 % of sRGB.

2 Process flow of full-color micro-LED display

The fabrication process of a color-converted full-color micro-LED display is shown in Fig.1. In the first step, a semiconductor based blue micro-LED arrays with pixel pitch of 12.8 μm and size of 8 μm was fabricated on a GaN-on-silicon substrate. In the second step, the blue micro-LED array was flip-chip bonded to a CMOS backplane by thermal-compression method and then followed by silicon substrate removal. Next, a color conversion layer was formed with patterned quantum dot patterns, color filter layer and the black matrix frame that can prevent optical cross talk between pixels. All the patterns were formed with photolithography process. In the final step, the color conversion layer was integrated to the blue light source with flip-chip bonding, and a full-color micro-LED array is finished.

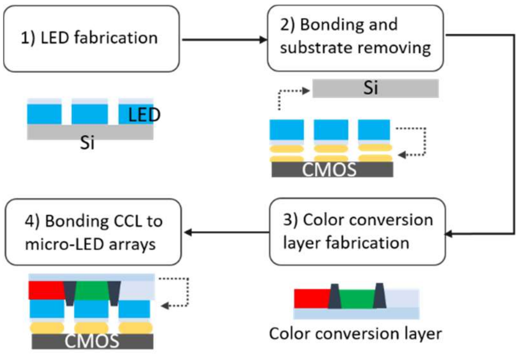

Fig. 1 Process flow of full-color micro-LED display.

3 Structure of color-converted micro-LED array

The detail structure of a color-converted micro-LED array is shown in Fig.2. Red and green quantum dots were mixed with photoresist separately and patterned on a glass substrate by the photolithography process [3]. The quantum dot patterns are 10 x 10 μm each in size and around 2 μm of thickness. Due to the limitation of quantum dot thickness and the quantum efficiency at the moment, blue light cannot be totally absorbed and transferred to red or green light. Therefore color filters of red and green are needed to cover above quantum dot pixels to cut the unabsorbed blue light. Color filter not only cut off the blue light which could not be transferred, but also filter the light form the neighbor sub-pixels.

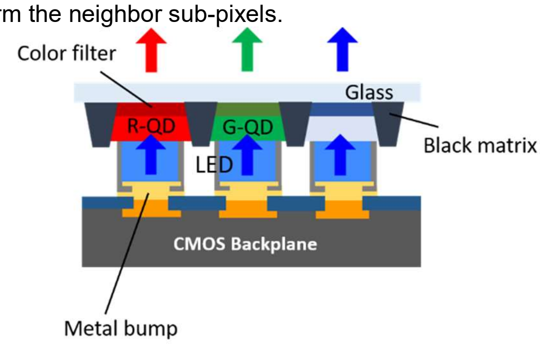

Fig. 2 Structure scheme of a pixel of color-converted micro-LED display.

Optical cross-talk issue become severe in fine-pitch micro-display [7]. Since the light emission from quantum dot pattern is isotropic, to place a black matrix between quantum dot sub-pixels is necessary for cross-talk reduction. The black matrix was formed with carbon-black photoresist and patterned as light shielding frame with 2.8 μm in width and 2.5 μm in height. The combination of quantum dot patterns, color filters and black matrix together formed a color conversion layer and would be integrated to the blue micro-LED array with precise alignment to build a color-converted full-color micro-LED array.

4 Result and Discussion

4.1 Performance of full-color micro-LED display

Result of a 0.55 inch color-converted micro-LED display with a resolution of 992 ppi, and 480x270 pixels is demonstrated in Fig.3. with designed word image in white light. The white light showed the result of combination of RGB light. This micro-display can present designed images and animations taking the advantages from the compact CMOS driver circuitry underneath and in periphery area, and specific algorithm is needed to coordinate the pictures demonstrated. Further optimization in the animation algorithm for this driving circuitry is needed to have a better demonstration.

Fig. 3 White light image of 0.55 inch color-converted micro-LED display with 992 ppi resolution

Fig. 4 shows a closer look into RGB pixels inside the color-converted micro-display. Each of red and green sub-pixel is 10 μm of size and the blue light opening is 8 μm in size.

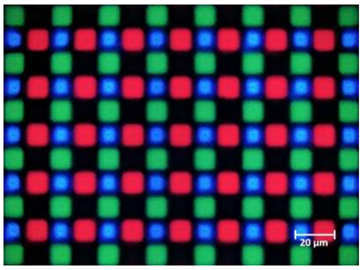

Fig. 4 Microscope image of RGB sub-pixels of color-converted micro-LED display

The color gamut of color-converted micro-LED display in CIE1931 color diagram is shown in Fig.5 and Table.1. The RGB color coordinates are (0.62, 0.29), (0.18,0.77), and (0.11, 0.13). The area of RGB triangle is shown as yellow line. If only the area is compared, the RGB area of this display equals to100 % of NTSC and 141 % of sRGB. But if we take the overlap area into consideration, the coverage is 84 % of NTSC and 83 % of sRGB. One of the reason for the less-than-expected coverage is due to the residual blue intensity in the red and green sub-pixels, which can greatly influence the color coordinates. If we can eliminate these blue residual intensity, or the optical cross-talk, the overlap between the current display and the NTSC/BT2020/sRGB area can be remarkably enhanced. As shown in the figure, the color gamut can be extended to the red line triangle and increase to gamut ratio to 110 % of NTSC and 155 % of sRGB. Currently the blue intensity is probably too strong for red and green, and with individually addressable driving capability of blue micro LED arrays, it is possible to control these sub-pixel to optimize the color gamut at present stage. Nevertheless, how to reduce this optical cross-talk will be the main issue when we move to next level.

Table. 1 Color coordinates and color gamut of color-converted micro-LED display

	Color coordinates			Color gamut ratio		
		x	y	BT2020	NTSC	sRGB
With optical cross-talk	R	0.620	0.285	74.7%	100%	141%
	G	0.182	0.773	Color gamut coverage		
	B	0.106	0.134	71.8%	83.7%	82.8%
	Color coordinates			Color gamut ratio		
Without optical cross-talk	R	0.644	0.650	82.0%	110%	155%
	G	0.182	0.773	Color gamut coverage		
	B	0.140	0.06	82.0%	96.5%	94.9%

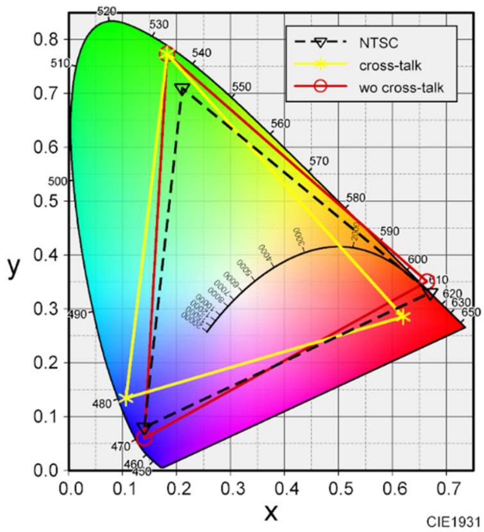

Fig. 5 Color gamut of color-converted micro-LED display

5 Conclusions

In the present article, we demonstrate the recent progresses and result of our 992 ppi full-color micro-display. The display based on quantum dot color conversion and micro-LED technology and showed a color gamut over 83% of NTSC coverage. The optical performance can be further improved if the optical cross-talk between sub-pixels can be avoided. The novel integration micro-display shows promising potential for future near-eye application in AR/MR.

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