

Ultra-High-Resolution Active-Matrix NanoLED Microdisplay by UV Photolithography

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Abstract

We report and discuss the challenges to realize ultra-high-resolution NanoLED on Si CMOS backplane. Quantum dot layers are patterned side-by-side by UV photolithography. We demonstrate a full-color 1.03 inch active-matrix NanoLED microdisplay with pixel density of 3,528 ppi and a wide color gamut over 120 % as a ratio to DCI-P3. This is the world's highest resolution self-emitting active-matrix device created by patterning red, green, and blue quantum dots.

Author Keywords

QD-LED; QLED; QD-EL; electroluminescence; quantum dot; microdisplay; AR/VR

1. Introduction

In recent years, along with the market growth of augmented reality (AR) and virtual reality (VR), research and development of microdisplays mounted on AR/VR devices has been actively carried out. Microdisplays for AR/VR require small panel size, high-resolution, high brightness and wide color gamut. To meet this demand, several types of microdisplays have been proposed. OLED microdisplay with color filters (CF) uses a silicon wafer-based CMOS backplane and a white OLED with a top emission structure as a frontplane, and red, green, and blue CFs are formed on the white OLED to achieve full color. The OLED microdisplays with these configurations are capable of providing ultra-high resolution displays¹, and displays with a resolution of 4,000 ppi have already been commercialized. However, there is still room for improvement from the viewpoint of widening the color gamut and increasing the brightness².

Two next-generation microdisplay technologies have recently been proposed in order to pursue wider color gamut and higher

brightness. The first is an OLED microdisplay that directly patterns red, green, and blue organic light emitting layers. Ghosh et al. developed a 2k x 2k Full-Color OLED microdisplay by directly patterning organic light emitting layers by photolithography³. The pixel dimension of this display is 9.3 μ m square, which corresponds to a pixel density of 2,731 ppi. Sugisawa et al. reported a photolithography process for RGB side-by-side patterning for OLED microdisplays and demonstrated a prototype with pixel density of 3,207 ppi and high brightness over 15,000 nit⁴. Kim et al. developed a manufacturing technology for fine metal masks that can handle up to 3,000 ppi⁵. In either method, the red, green, and blue organic light emitting layers are directly patterned, so color gamut and brightness are expected to improve compared to OLED microdisplay with CF. The second is a microLED microdisplay which arrange microLEDs on a Si wafer-based CMOS backplane. Due to the difficulty of the technical hurdle of arranging red, green, and blue LEDs with high resolution for full color, the method of forming a color conversion layer is mainly proposed⁶⁻⁹. The quantum dots (QDs) of each color are placed on the red and green sub-pixels for color conversions, after arranging blue microLEDs.

NanoLED displays (sometimes referred to as 'QD-LED', 'QLED' or 'QD-EL') use electroluminescence of QDs to produce directly the three primary colors in each pixel. They have the potential of high brightness, high contrast, high resolution, and to be made on rollable or flexible substrate with lower cost than OLED¹⁰⁻¹¹. We have already reported that active-matrix NanoLED using three primary color QDs patterned by photolithography¹². We also demonstrated a photolithography patterning of QDs with high resolution of 3,996 ppi using a passive test device fabricated on Si substrate¹³. In this paper, as a

Table 1. Comparison of basic expected characteristics of display technology for microdisplays.

	White OLED with CF	Direct Patterned OLED	Blue μ LED with QD-CC	NanoLED
Structure				
Resolution	> 4,000 ppi	> 3,200 ppi	> 4,000 ppi	> 3,500 ppi
Brightness	< 10,000 nit	> 15,000 nit	>300,000 nit	>15,000 nit
Color Gamut	< 97% (DCI-P3)	< 100% (DCI-P3)	< 106% (NTSC)	< 123% (DCI-P3) < 118% (NTSC)

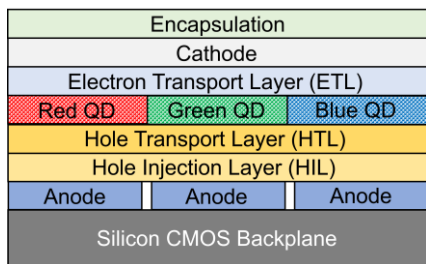


Figure 1. Structure of Active-Matrix NanoLED.

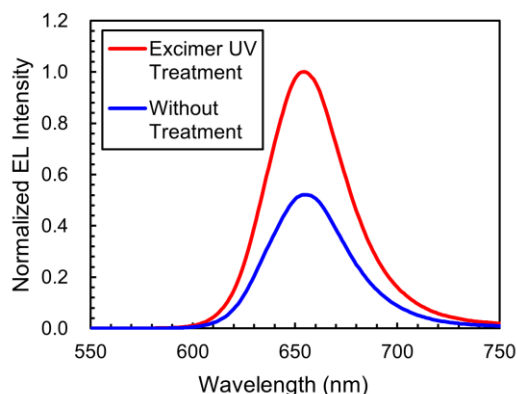


Figure 2. Emission spectra of the samples with excimer UV treatment and without treatment on anode electrodes.

new type of microdisplay, we report ultra-high-resolution NanoLED fabricated on active-matrix Si CMOS backplane.

2. Contents and Results

Display Method Comparison:

We will discuss the comparison of each microdisplay method introduced in the previous section. Table 1 shows the general structures and the basic expected characteristics of each display method. The white OLED with CF realizes a high resolution but has challenges with the brightness and color gamut. Most of the white light emitted from the OLED layer is absorbed by the color filter, which causes a decrease in brightness. In addition, it is difficult for color filters to completely absorb unnecessary light, and it allows colors other than the desired primary colors to pass

through, resulting in a decrease in color gamut. The direct patterned OLED has an organic light emitting layer formed for each red, green, and blue color, so it is possible to improve the brightness and color gamut compared to white OLED with CF. However, it is necessary to improve the direct patterning technology in order to achieve higher resolution. The blue microLED with QD color conversion layers can drive the microLED with high current density, so it is expected to achieve the highest brightness among these methods. QD itself has high potential for wide color gamut, but at this stage, the color gamut remains at the same level as OLED because the absorbance of QD color conversion layers for blue excitation light is not sufficient. Color filters are required to absorb blue light leaked from QD color conversion layers. NanoLED has the same structure as direct patterned OLED, so it is possible to realize high brightness and wide color gamut. Also, because NanoLED can utilize the narrow emission spectrum peculiar to QD electroluminescence, it is more advantageous than the direct patterned OLED and microLED in terms of the wide color gamut. Furthermore, photolithography patterning technology of QD we have developed is suitable for fabricating ultra-high-resolution displays.

Device Fabrication:

We utilized Si CMOS backplanes for the fabrication of high resolution NanoLED panels which have structure as shown in Figure 1. The Si CMOS backplanes were cleaned with acetone and isopropyl alcohol. Subsequently, excimer UV was used for surface treatment of anode materials before coating HIL. After HTL was coated, QD layers with red, green, and blue colors were coated by solution process and patterned side-by-side with UV photolithography. After ETL was coated on the patterned QD layers, cathode electrode was deposited. Then the device was encapsulated with glass lid under inert atmosphere.

Results:

Figure 2 shows the emission spectra of the samples with excimer UV treatment and without treatment on anode electrodes. The EL device with UV treatment shows higher EL intensity than that without treatment. In appearance, the sample without treatment showed unevenness on the luminous surface, but the sample with excimer UV treatment showed no unevenness. Excimer UV treatment is a technology that has the effect of removing organic materials¹⁴. We presume that organic contamination material remained on the anode electrode surface of the sample without the treatment despite cleaning with acetone and isopropyl alcohol, but it was removed on the anode electrode surface of the sample with excimer UV treatment. The organic contamination material creates the problem of interfering with hole injection from anode

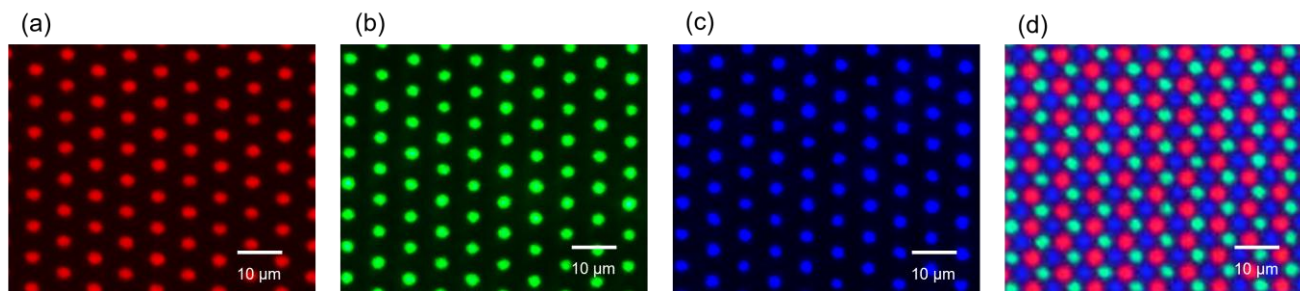


Figure 3. The electroluminescent micrographs of the 3,528 ppi NanoLED pixels.

(a) Red, (b) green, (c) blue and (d) RGB pixels emitted.

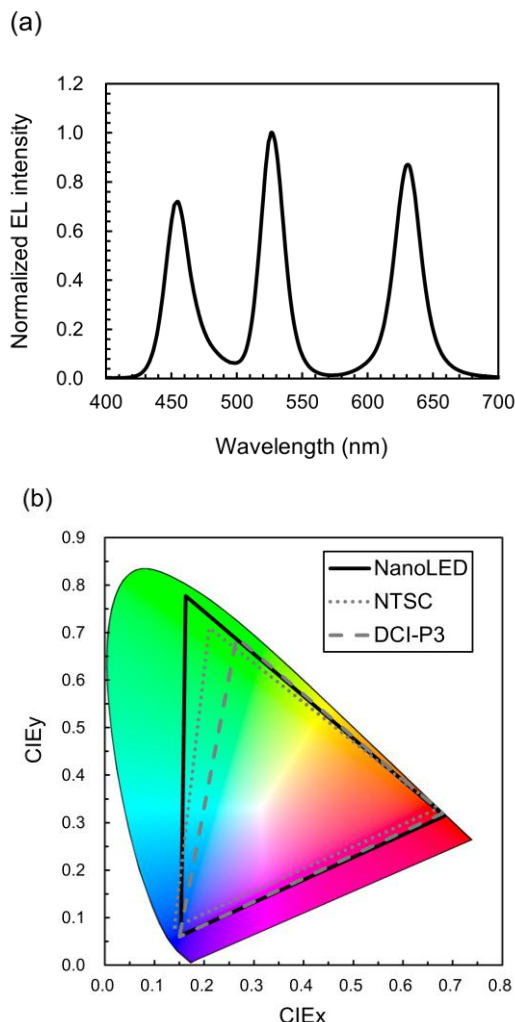


Figure 4. (a) Emission spectra of the NanoLED microdisplay at white. (b) Color coordinates of R, G, B subpixels of the NanoLED microdisplay. The solid line triangle corresponds to the color space of emissive light from the NanoLED sample, the dotted line triangle stands for the NTSC standard, and the dashed line triangle stands for the DCI-P3 standard, each drawn in CIE 1931 color space.

Table 2. Color coordinates for NanoLED microdisplay.

Color	CIE _x	CIE _y	Area Ratio to DCI-P3 (%)	Area Ratio to NTSC (%)
Red	0.68	0.31	123.7	118.9
Green	0.16	0.78		
Blue	0.15	0.06		

to HIL, but the excimer UV treatment was found to solve this problem. Because the interface between anode electrode and HIL is important for NanoLED device, we applied excimer UV treatment for the fabrication of the active-matrix NanoLED devices.

Table 3. Specifications of the NanoLED microdisplay in this work.

Parameter	Specifications
Panel size	1.03 inch
Resolution	2,560 x 2,560
Pixel geometry	Delta
Pixel pitch	7.2 μm
Pixel density	3,528 ppi
Patterning	Side-by-Side by Photolithography
Display Type	Top-emission AM NanoLED
Color	> DCI-P3 120%



Figure 5. Picture of a 1.03-inch Active-Matrix NanoLED Microdisplay with 3,528 ppi.

Figure 3 shows electroluminescent micrographs of the active-matrix in which red, green and blue NanoLEDs are formed in delta pixel geometry on the same substrate. Figure 3 (a), (b) and (c) show electroluminescent micrographs of red, green, and blue subpixels individually emitted by active-matrix circuits, respectively. Figure 3(d) shows an electroluminescent micrograph of red, green, and blue subpixels emitted simultaneously. The pixel density is 3,528 ppi and pixel pitch is 7.2 μm .

Figure 4(a) shows an example of the EL spectrum of the NanoLED panel at white. Three peaks that correspond to red, green, and blue QD emission were observed. Figure 4(b) and Table 2 show the color coordinates of R, G, B subpixels of a NanoLED panel. The color gamut of the NanoLED panel reached up to 123.7% as area ratio to DCI-P3 and 118.9% as area ratio to NTSC. This wide color gamut is an advantage of NanoLED compared to other type of microdisplays.

Table 3 shows the specification of the NanoLED panel. Figure 5 shows the picture of the NanoLED panel. This is the world's highest resolution self-emitting active-matrix device created by patterning red, green, and blue quantum dots side-by-side.

3. Conclusion

As a next-generation microdisplay for AR/VR, we introduced NanoLED technology that can simultaneously realize high resolution and wide color gamut. We demonstrated a 1.03 inch active-matrix NanoLED microdisplay with pixel density of 3,528 ppi by patterning quantum dot layers with photolithography. The NanoLED device showed a wide color gamut up to 123.7% DCI-P3 due to narrow emission characteristics of quantum dots. The NanoLED technology is a promising technology for high-quality AR and VR displays realizing immersive user experiences.

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