Ultra-High-Brightness 2K x 2K Full-Color OLED Microdisplay Using Direct Patterning of OLED Emitters

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Abstract

The performance details of a full-color 2K x 2K resolution OLED microdisplay with a brightness of 5,000 cd/m^2 will be presented. The microdisplay was built on a CMOS-based silicon backplane using direct patterning of the primary-color OLED emitters. Additionally, the color gamut of the microdisplays were increased to meet sRGB requirements. Such microdisplays will be ideally suited for wearable VR (virtual reality) and AR (augmented reality) applications.

Author Keywords

OLED; AMOLED; microdisplay; augmented reality; virtual reality; high resolution; head-mounted display

1. Introduction

Immersive virtual reality (VR) and augmented reality (AR) wearables require displays with high luminance and high resolution. In addition, excellent contrast, wide color gamut and high pixel density coupled with low power consumption and light weight are also needed. While cell phone-type displays are used in many VR applications today, the low pixel density (typically around 500 ppi) and fill factor can create a 'screen door' effect in which the dark space between pixels is visible. Further, these devices are not currently capable of achieving the high luminance required for both VR and AR.

OLED microdisplays are capable of generating high quality images that meet many of the requirements of VR/AR applications [1-7]; however, the maximum luminance of conventional full color OLED microdisplays remains below the 2,000 cd/m2 minimum threshold requirement of VR/AR. The luminance is limited by the device's structure; all conventional full color OLED microdisplays use a broad spectrum fluorescent white OLED in conjunction with red, green and blue (RGB) color filters patterned or placed on top of the OLED (after thin film encapsulation) to achieve full color emission (Figure 1a). However, the overall luminance is decreased by up to 80%.

Eliminating the color filters and directly patterning individual side-by-side red, green and blue OLED emitters (Figure 1b) offers significant improvements in efficiency and luminance, especially if phosphorescent materials are used. However, the small subpixel size (typically ~3 micron x ~10 micron) presents a major technological hurdle as the patterned dimensions are below that achievable by standard fine metal masks. Though there have been significant efforts to develop the capability to pattern organics at such a fine scale it was only in 2016 that the first working directly patterned (DP) RGB OLED microdisplay with sub-10-micron pixel sizes was demonstrated, reaching luminance of >3,500 cd/m^2 [8]. This work utilized a WUXGA resolution CMOS backplane designed for conventional OLED microdisplays with white OLED emitter and color filters. In this paper, a new high resolution 2K x 2K CMOS silicon backplane is reported with individual corrections for each color channel, which allows the utilization of the differing efficiencies and IV characteristics of each color emitter in a true RGB display. Further, the DP display performance is advanced through improvements to the device luminance and the introduction of color enhancement layers leading to an expanded color gamut exceeding the sRGB and approaching the DCI-P3 standard.

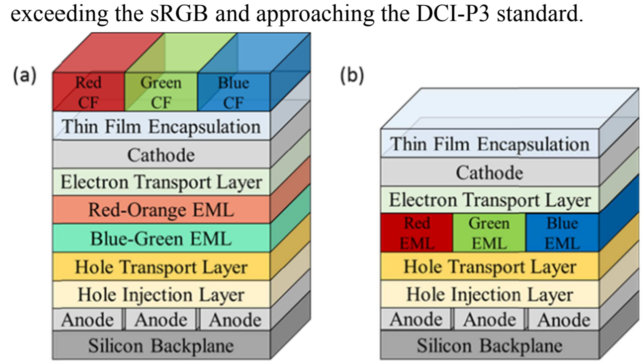

Figure 1. Structure of (a) conventional white OLED with color filter (CF) array in comparison with a (b) directly patterned OLED with red, green and blue emitter layers (EML) eliminating the need for color filters. From Ref 8.

2. Approach

2K x 2K Silicon Backplane

In order to fully exploit the capabilities of the novel side by side DP OLED technology, a new backplane architecture has been developed with full color 2K x 2K resolution. The backplane has been designed to deliver high peak luminance, wide dynamic range, high frame rates, and variable persistence operation with both rolling and global shutter options. A luminance output of more than 60,000 cd/m^2 has been measured for a monochrome green OLED display, demonstrating the capability of the backplane to drive the OLED array to very high brightness levels. The backplane also includes a new 4T-1C pixel driver circuit that supports high pixel density and improved silicon manufacturability, and is built in an advanced 180nm CMOS foundry process with dual 1.8/5V capability. The features provided by the combination of OLED DP technology and the new backplane platform are aimed at meeting the requirements of future wearable VR and AR applications. A block diagram of the backplane architecture is given in Figure 2.

A key requirement of the new backplane design was to achieve maximum compatibility with the wide field of view optical solutions that might be used for near to eye immersive systems. As a result, the pixel size selected for the array was the largest that would allow the 2K x 2K design to be patterned by standard semiconductor lithography tools without the use of stitching. The color pixel pitch is 9.3x9.3 um and the overall die size is 21.91x21.88 mm with a viewing diagonal of 26.94mm (1.06").

 ISSN 0097-996X/17/4701-0226-$1.00

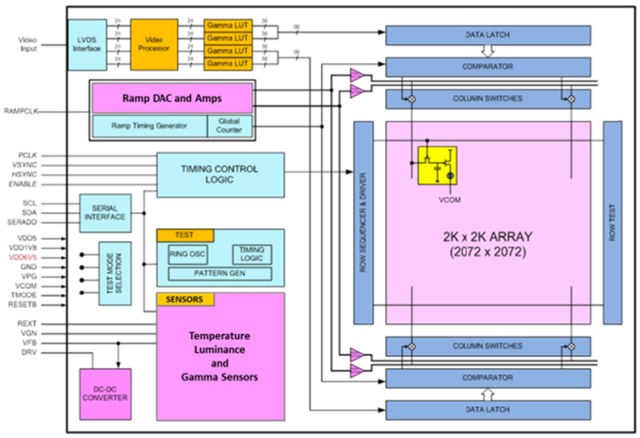

Figure 2. 2K x 2K block diagram.

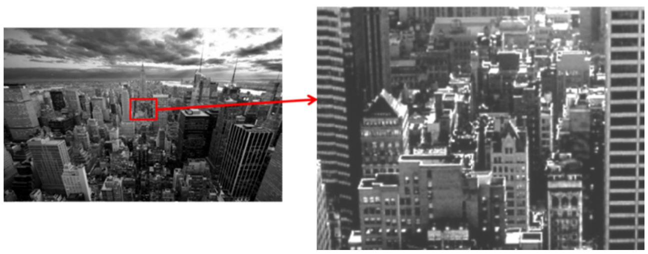

Figure 3. Close-up photo of a 2K x 2K monochrome display.

This is the largest microdisplay built by eMagin to date with over 12.9 million individual color dots. A photo of a monochrome display image shown in Figure 3 demonstrates the high resolution capability of the 2K x 2K display.

The backplane was designed with the flexibility to support a variety of color pixel layouts including RGB vertical stripe and RGBB quad-type design configurations. This was done so that the tradeoffs between optical performance and OLED fabrication for different sub-pixel arrangements could be tested and evaluated. Some of the sub-pixel layouts that have been explored are shown in Figure 4. These range from the standard RGB stripe on the left to the rotated RGBB structure on the right where sub-pixels of the same color are adjacent to each other.

The on-chip digital video receiver is comprised of 13 low voltage differential signaling (LVDS) data channels and one clock channel that are compatible with standard field programmable gate array (FPGA) LVDS drivers. It is based on a proprietary low-power design which includes functions for clock recovery, channel de-skew, and data deserialization. In addition to the full-function color mode, the LVDS receiver offers a reduced-power monochrome mode that requires only 5 data channels and one clock channel to allow the option of a simplified cable design for driving the display.

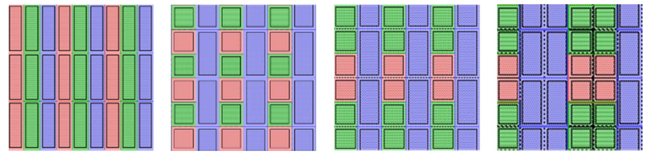

Figure 4. Examples of 3 x 3 color pixel configurations.

Of particular importance to wearable VR systems is the need to manage motion artifacts that result when fast eye or head movements are performed with displays running at typical frame rates. One of the benefits of OLED technology is the ability to update the image at extremely fast rates compared to alternative displays such as LCD, enabling low persistence operation to be implemented for reducing motion blur. In addition DP allows low persistence to be achieved while still providing high average luminance to the eye. To exploit this feature the 2K x 2K backplane design includes two methods of persistence control. The rolling shutter option is generated via pulse width control on a row by row basis. In this approach a portion of the display is always lit, consisting of a group of rows that is moving across the display from top to bottom at the frame rate. The number of rows that is lit at any time can be set independently by the user and defines the persistence of the display. A benefit of this approach is that there is no additional timing overhead required so the display can run at the maximum frame rate. A summary of key features is listed in Table 1.

Global shutter mode is the second type of persistence control that is implemented in the 2K x 2K design. In this approach the display is completely off while the pixels are being updated with fresh data. After the full frame of data is written, the entire array of pixels is turned on simultaneously for a period that determines the persistence time. The 2K x 2K display provides a global shutter pin that is used to turn the full array of pixels on and off simultaneously using a pixel level control signal. No external frame memory is required as the pixel memory is used to store image during the write time when emission is off. Any range of shutter control is possible from 100 to <10% persistence. A consequence of this method is the need for additional time beyond the normal frame period in order to illuminate the array, causing a reduction in the maximum available frame rate.

Table 1. Summary of 2K x 2K features

Parameter	Value	Parameter	Value
Array Resolution	2048 x RGB x 2048	Video Interface	Serialized low-power LVDS
Extra Pixels for Optical Alignment	24 rows and columns	24-bit RGB mode	13 data + 1 clock channels
Pixel Dimensions	9.3 um square	8-bit monochrome mode	5 data + 1 clock channels
Diagonal Viewing Area	26.94 mm (1.06")	LVDS Data Bandwidth	>12 Gbps
Die Size	21.91 x 21.88 mm	Video Source Clock	118.5 MHz
Backplane Technology	180nm CMOS 1.8/5V	Refresh Rate	30 to >90 Hz
Gray Levels	256 per primary color	Horizontal Picture Shift	255 pixels in 1 pixel steps
Contrast Ratio	>10,000:1	Vertical Picture Shift	511 lines in 1 line steps
Supported Video Modes	2K x 2K (2048 x rgb x 2048)	Dimming Ratio (analog)	500:1
	QXGA (2048 x rgb x 1536)	Rolling Shutter Persistence	<1 to 100%
	WUXGA (1920 x rgb x 1200)	Global Shutter Persistence	<10 to 100%
	HD1080 (1920 x rgb x 1080)	Gamma Correction Function	On-Chip separate RGB
	UXGA (1600 x rgb x 1200)	Host Interface	2 wire serial (I2C)

One of the primary challenges for any side-by-side OLED display is to provide accurate gray axis color uniformity, particularly when the individual RGB sub-pixels are based on materials with differing LIV characteristics. To achieve the proper gamma setting for all gray levels may require independent pixel voltage as well as separate gamma control for each color. This requirement is addressed in the 2K x 2K backplane by providing on-chip sensors that monitor the IV characteristics of each color and including separate gamma correction functions. As opposed to using an external color correction approach, the method developed in the 2K x 2K can achieve 24bit color accuracy for the entire gray axis over a wide luminance and temperature range.

Directly Patterned 2K x 2K Microdisplay

This 2K x 2K silicon backplane formed the foundation of a top emitting DP OLED microdisplay. A pixelated, highly reflective metal anode was formed on top of the silicon backplane in the pixel layout indicated to the right in Figure 4. Though previous efforts have patterned subpixels as small as 1.95 micron x 7.8 micron, this rotated RGBB pixel structure would allow for simultaneous patterning of either four red / green subpixels (3.5 µm x 3.35 µm sized subpixels) or two larger blue subpixels (3.3 µm x 7.85 µm sized subpixels). The overall fill factor is 57%.

On top of the anode, the organic structure indicated in Figure 1b was deposited. All common organic and cathode layers were evaporated using conventional large opening metal masks. Only the RGB emitter layers were directly patterned using eMagin's proprietary DP technology - though future systems could allow for the patterning of entire unique OLED stacks for each color. A fluorescent blue emitter was used in conjunction with phosphorescent red and green (Universal Display Corporation). Displays were encapsulated, processed and packaged following a standard process flow with no significant change to processes other than the directly patterned emitter layers. Measurements on packaged displays were taken using a Photo Research PR680 spectroradiometer/spectrophotometer (spectra and color coordinates) or a Minolta CS-100A (luminance).

3. Results

Directly Patterned 2K x 2K OLED Microdisplay

An image of a full color 2K x 2K microdisplay running test patterns is shown on the left side of Figure 5. The right image of Figure 5 shows a close-up image of directly patterned pixel configuration taken under a high magnification optical microscope. Figure 6 shows luminance versus array current measured with 50% of pixels on. The blue diamonds show measured data with the solid line extrapolating past 100 mA. This extrapolation was necessary due to a current limitation in the initial drive board that prevented currents past 100 mA. The next generation of drive board will allow higher currents and luminance. With a reduced window size (12.5% pixels on), luminance of over 5,000 cd/m^2 was achieved using the advanced backplane. Figure 7 shows the individual color spectra for the directly patterned 2K x 2K microdisplay with corresponding color coordinates listed in Table 2. As can be observed, each directly patterned color is distinct and close to the inherent material spectra.

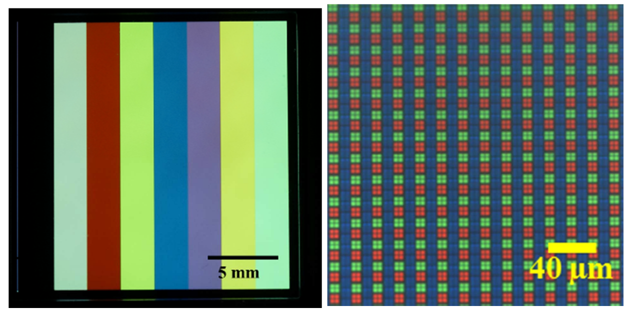

Figure 5. Image of full color DP 2Kx2K microdisplay (left) and close-up image of emission from patterned OLED array (right).

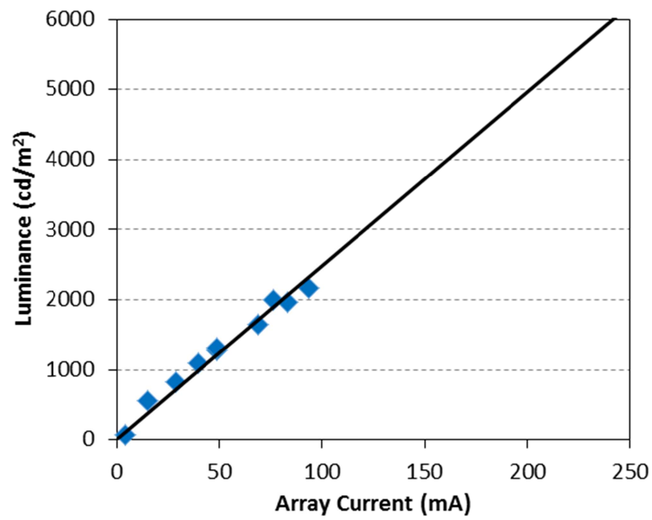

Figure 6. Luminance versus array current with 50% of the pixels on, where the solid line is the extrapolation to high brightness.

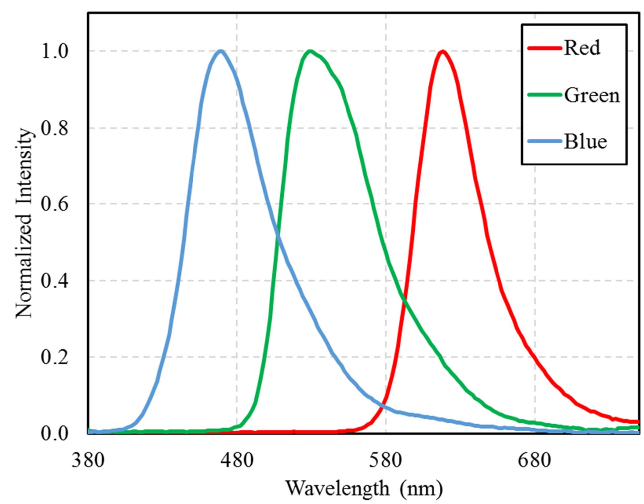

Figure 7. Individual red, green and blue spectra from DP 2K x 2K OLED microdisplay.

Table 2. Color coordinates for directly patterned 2K x 2K OLED microdisplay

Color	CIEx	CIEy	% DCI-P3	% sRGB
White	0.309	0.419	58.6	79.5
Red	0.656	0.338		
Green	0.343	0.616		
Blue	0.157	0.212		

Enhanced Color Gamut on WUXGA Backplane

In addition to the development of a DP 2K x 2K, progress was made in significantly enhancing the color gamut of existing DP WUXGA displays. The process discussed previously [8] was followed in conjunction with the introduction of additional color enhancement layers that served to narrow and shift each individual color emission to more saturated color coordinates. This process was applied to WUXGA DP OLED microdisplays though it can be readily applied to the 2Kx2K DP OLED microdisplays discussed here.

The effect of these layers are demonstrated in Table 3 and Figure 8 which show data from identical processing other than the color enhancement layer. Color coordinates are shifted to more fully saturated values, and the enhanced gamut DP OLED microdisplay reaches 133% of sRGB color gamut compared to 86.3% for the standard process (Table 3). These more saturated colors are somewhat less efficient than the standard DP counterpart and for the same active drive settings, the display with the enhanced color gamut emits 35-45% less light than its standard DP counterpart. However, future work will increase the luminance further to compensate for this loss.

Table 3. Color coordinate comparison between standard and enhanced gamut directly patterned WUXGA microdisplay

Color	Standard DP (Control)			
	CIEx	CIEy	%DCI-P3	%sRGB
Red	0.649	0.346	63.6	86.3
Green	0.322	0.630		
Blue	0.148	0.190		

Color	Enhanced Gamut DP			
	CIEx	CIEy	%DCI-P3	%sRGB
Red	0.673	0.324	98.0	133.0
Green	0.258	0.683		
Blue	0.135	0.071		

4. Conclusions

A full color directly patterned 2K x 2K OLED microdisplay using an advanced backplane was demonstrated. This high resolution backplane incorporates high frame rates, individual color gamma control and variable persistence operation with both rolling and global shutter options. A maximum luminance of 5,000 cd/m^2 was achieved with a color gamut of 80% sRGB. This color gamut can be improved through a color enhancement layer demonstrated on directly patterned WUXGA OLED microdisplays to achieve 133% sRGB and 98% DCI-P3.

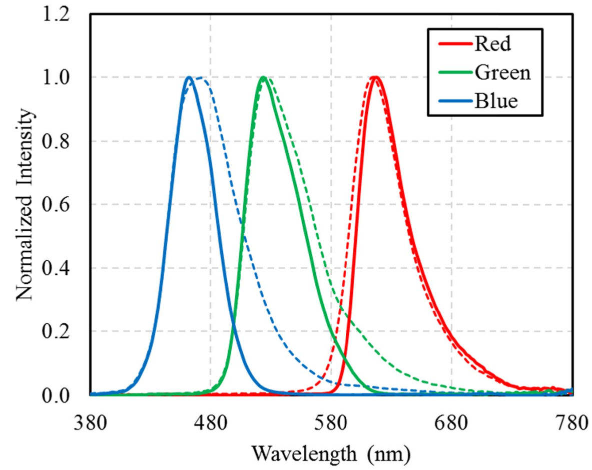

Figure 8. Emission spectra for both standard (dashed line) and enhanced (solid line) directly patterned WUXGA OLED microdisplays.

5. Acknowledgements

The U.S. Army Night Vision and Electronic Sensors Directorate (NVESD) and Defense-wide Manufacturing Science and Technology (DMS&T) are gratefully acknowledged for their support of this work. The contributions from Andrew Sculley, James Steeves, Scott Ziesmer, Chris Yelvington, Mike McQueen and the staff of eMagin are gratefully acknowledged.

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